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Applied Electrochemistry
25/02/2012 → present
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Publications:

Durable fuel electrode
The present invention relates to a composite for an electrode, a composite precursor, a method of manufacturing a composite, and the composite obtained by said method. The invention further relates to an electrode comprising the composite, as well as a solid state electrochemical cell comprising the composite. The invention also relates to the use of the composite as a fuel electrode, solid oxide fuel cell, and/or solid oxide electrolyser. The invention discloses a composite for an electrode, comprising a three-dimensional network of dispersed metal particles, stabilised zirconia particles and pores, wherein the size of the pores is smaller than the size of the metal particles, wherein the size of the metal particles is essentially equal to or smaller than the size of the stabilised zirconia particles, wherein the porosity is below 33, 30, or 29 vol\%, more preferably below 26 or 24 vol\%, and most preferably below 23, 22, 21, 18, 15, or 13 vol\%, and/or wherein the pores are essentially exclusively generated from the volume created by reducing a corresponding metal oxide to the metal particles.

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Solid oxide electrolysis cells (SOECs) can efficiently convert electrical energy (e.g. surplus wind power) to energy stored in fuels such as hydrogen or other synthetic fuels. Performance and durability of the SOEC has increased orders of magnitudes within the last decade. This paper presents a short review of the R&D work on SOEC single cells conducted at DTU Energy from 2005 to 2015. The SOEC improvements have involved increasing the of the oxygen electrode performance, elimination of impurities in the feed streams, optimization of processing routes, and fuel electrode structure optimization. All together, these improvements have led to a decrease in long-term degradation rate from ~40 %/kh to ~0.4 %/kh for steam electrolysis at -1 A/cm², while the initial area specific resistance has been decreased from 0.44 Ωcm² to 0.15 Ωcm² at -0.5 A/cm² and 750 °C.
Concentration Impedance in Testing of Solid Oxide Cells Revisited

The concentration impedance originating from diffusion and reactant conversion impedance of the Ni-YSZ supported fuel electrode in solid oxide cell has been treated many times during the latest couple of decades. In spite of this, the separation of the diffusion impedance from the conversion impedance is still not trivial. Therefore, combined theoretical and experimental methods available for breakdown of the concentration impedance are outlined and discussed.
High performance LaNi_{1-x}Co_{x}O_{3-δ} (x = 0.4 to 0.7) infiltrated oxygen electrodes for reversible solid oxide cells

Oxygen electrodes prepared by infiltration of yttria stabilized zirconia backbone with Ce_{0.8}Gd_{0.2}O_{1.95} barrier layer and LaNi_{1-x}Co_{x}O_{3-δ} (x = 0.4 to 0.7) catalyst for application in reversible solid oxide cells have been studied. The effect of temperature and Ni:Co ratio on their phase composition, microstructure and electrochemical properties are discussed. It was shown that oxygen electrodes infiltrated with LaNi_{0.5}Co_{0.5}O_{3-δ} had the lowest polarization resistance, i.e. 67 mΩ cm² at 600 °C. The performance of a fuel electrode supported solid oxide cell with infiltrated oxygen electrode in both fuel cell and electrolysis mode was tested. Electrochemical characterization of the solid oxide cell showed that the resistance contribution from these oxygen electrodes to the overall cell resistance is minor i.e. approximately 20 mΩ cm² at a temperature of 700 °C. The cell was also tested in the steam electrolysis mode at a constant current of −1.0 A cm⁻² at 800 °C for 240 h. The oxygen electrode showed reasonable degradation rate with the oxygen electrode resistance of 33 mΩ cm² at 700 °C after 240 h of testing.
Microstructural Characterization of Ni/YSZ Electrodes in a Solid Oxide Electrolysis Stack Tested for 9000 Hours

The effects of long-term operation in electrolysis mode on the microstructure of Ni/YSZ electrodes were investigated. The electrode structures were investigated in “as reduced” state and after 9000 h of operation in a 25 cell stack. Microstructural data were obtained by scanning electron microscopy and focused-ion-beam serial sectioning. Microstructural characteristics were extracted by 1D and 3D methods. Significant microstructural changes were observed between the two cells analyzed. A significant loss of Ni in the active electrode is observed, from ~29% (by volume) in the reference cell to ~24% as well as a coarsening of the Ni particle sizes. The long-term tested cell shows lower percolating triple phase boundary density (0.76 μm/μm^3) than the un-tested reference (2.0 μm/μm^3). This reduction is mainly due to the loss of triple phase boundary percolation through the Ni phase where a reduction from a percolation degree above 90% to ~50% is observed.

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Microstructural Characterization of Ni/YSZ Electrodes in a Solid Oxide Electrolysis Stack Tested for 9000 Hours

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Relation Between Ni Particle Shape Change and Ni Migration in Ni–YSZ Electrodes – a Hypothesis

This paper deals with degradation mechanisms of Ni–YSZ electrodes for solid oxide cells, mainly solid oxide electrolysis cells (SOECs), but also to some extent solid oxide fuel cells (SOFCs). Analysis of literature data reveals that several apparently different and even in one case apparently contradicting degradation phenomena are a consequence of interplay between loss of contact between the Ni–YSZ (and Ni–Ni particles) in the active fine-structured composite fuel electrode layer and migration of Ni via weakly oxidized Ni hydroxide species. A hypothesis that unravels the apparent contradiction and explains qualitatively the phenomena is presented, and as a side effect, light has been shed on a degradation phenomenon in solid oxide fuel cells (SOFCs) that has been observed during a decade.

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Study of Operating Parameters for Accelerated Anode Degradation in SOFCs

Solid oxide fuel cell (SOFC) applications require lifetimes of several years on the system level. A big challenge is to demonstrate such exceptionally long lifetimes in ongoing R&D projects. Accelerated or compressed testing are alternative methods to obtain this. Activities in this area have been carried out without arriving at a generally accepted methodology. This is mainly due to the complexity of degradation mechanisms on the single SOFC components as function of operating parameters. In this study, we present a detailed analysis of approx. 180 durability tests regarding degradation of single SOFC components as function of operating conditions. Electrochemical impedance data were collected on the fresh and long-term tested SOFCs and used to de-convolute the individual losses of single SOFC cell components – electrolyte, cathode and anode. The main findings include a time-dependent effect on degradation rates and the domination of anode degradation for the evaluated cell types and operating conditions. Specifically, the steam content as determined by fuel inlet composition, current density and fuel utilization was identified as major parameter, more important than for example operating temperature. The obtained knowledge is adopted to identify optimal operation profiles in order to acquire accelerated testing for lifetime investigation of SOFCs.

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Testing of Electrodes, Cells and Short Stacks

The present contribution describes the electrochemical testing and characterization of electrodes, cells, and short stacks. To achieve the maximum insight and results from testing of electrodes and cells, it is obviously necessary to have a good understanding of the fundamental principles of electrochemistry, but it also requires proper test geometries and set up, well-chosen operating conditions for different test purposes, correct probing of voltages and temperatures, and solid knowledge on benefits and drawbacks of different characterization techniques to obtain reliable, accurate, and reproducible electrochemical measurements, and this will be the focus of this chapter. First, the important issue of understanding potential differences and measurements of potentials, which is linked to the choice of proper electrode geometries and test set up configurations for electrode and cell testing, is presented. Then probing of voltages and temperatures, choice of sealing and contacting, as well as considerations regarding the choice of operating conditions for different purposes mainly for single cell testing are outlined. Having considered optimization of test set up, geometries, and the selection of optimal operating conditions, the details of measurement of the electrochemical performance of the electrode, cell, or stack are explained. As part of this, the concept of area specific resistance (ASR) and how DC and AC methods can be used and optimized to provide not only the total ASR, but also the electrochemical characterization of specific parts (electrolyte, each electrode) in a full cell are described. Some experimental results are provided including illustrative examples of breakdown of losses in full cells and determination of their temperature and gas composition dependencies, and finally, challenging issues, such as the effects of impurities and the problem of leakage in cell testing, are discussed as well.

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Towards long-term stable solid state electrolyzers with infiltrated catalysts

Renewable energy sources like wind and solar are widely considered as the key technologies to cover our growing demands. However, the fluctuating nature of these sources requires a flexible energy system and storage technologies to ensure that energy supply can be covered in a stable and affordable manner. One of the promising solutions is the production of synthetic fuel by solid oxide electrolyzers. Electricity can be converted to gas and further to liquid products during times of electricity production excess. In times of need, these fuels can be converted back to electricity by either conventional power plants or fuel cells.

Key challenges for a successful commercialization of solid oxide electrolyzers are upscale it, reduce cost and improve durability. Therefore, large efforts are allocated to improve cell performance. As a relatively novel method to introduce electro-catalysts into the porous structure of the electrodes, infiltration has shown very efficient. Solid oxide cells with infiltrated electrodes have been reported to show improved performance compared to conventional cells [1].

In this study, the development of infiltration procedures to improve the stability and catalytic performance of the fuel electrode of solid state electrolyzers (SOEC) will be presented. The infiltration process was optimized through choice of surfactants and concentrations of precursor solutions, to ensure easy penetration of the precursor solution into a Ni-YSZ (yttrium stabilized zirconia) composite backbone. The influence of surfactants on the coverage of specific grains with the infiltrated Ce0.8Gd0.2O2-d (CGO) nano-sized catalyst in the composite backbone was also studied. The optimized infiltration process was applied to 5 x 5 cm solid oxide cells.

The cells composed of a thin YSZ electrolyte, a Ni-YSZ fuel electrode and an LSCF-CGO oxygen electrode were tested in steam electrolysis operation under a current load of up to 1.25 A/cm2. Under high steam content and high current density, a fast cell degradation (~700 mV/kh) was observed for un-infiltrated cells. The infiltration of a CGO nano-sized catalyst into the Ni-YSZ backbone was observed to reduce the degradation rate to around 117 mV/kh.

A Decade of Improvements for Solid Oxide Electrolysis Cells. Long-Term Degradation Rate from 40%/Kh to 0.4 % Kh

Solid oxide electrolysis cells (SOEC) have the potential for efficient large-scale conversion from electrical energy to chemical energy stored in fuels, such as hydrogen or synthetic hydrocarbon fuels by use of well-known catalysis processes. Key issues for the break-through of this technology are to provide inexpensive, reliable, high performing and long-term stable SOEC for stack and system applications. At DTU Energy (formerly Department of Fuel Cells and Solid State Chemistry, Risø National Laboratory), research within SOEC for more than a decade has led to long-term degradation rates on cell level being improved from 40 %/kh to 0.4 %/kh for tests at -1 A/cm2. Under high steam content and high current density, a fast cell degradation (~700 mV/kh) was observed for un-infiltrated cells. The infiltration of a CGO nano-sized catalyst into the Ni-YSZ backbone was observed to reduce the degradation rate to around 117 mV/kh.
in-Situ Formed Ce₀.₈Gd₀.₂O₁.₉ Barrier Layer on Yttria Stabilized Zirconia Back-Bone for Infiltrated Oxygen Electrodes

Solid oxide cells (SOCs) would be economically more favorable with lower operating temperature. Currently the target temperature is between 550 °C and 750 °C. Such low operation temperatures would reduce thermally activated degradation phenomena and would allow the use of cheaper materials. However, reduction of the operating temperature increases the ohmic and electrode polarization losses of the cells.

New Hypothesis for SOFC Ceramic Oxygen Electrode Mechanisms

A new hypothesis for the electrochemical reaction mechanism in solid oxide cell ceramic oxygen electrodes is proposed based on literature including our own results. The hypothesis postulates that the observed thin layers of SrO-La₂O₃ on top of ceramic perovskite and other Ruddlesden-Popper structured electrode materials are sufficiently electron and oxygen ion conducting to provide reaction sites despite that the bulk phase of such an oxide layer is insulating. We claim that a few nanometer thin layer of mixed SrO-La₂O₃ that contains some dissolved transition metal and some impurities plus two space charge layers – one towards the gas phase and the other towards the perovskite – will be sufficiently oxide ion (vacancy) and electron conducting to support the electrode process. We also present some considerations about a possible mechanism of improved electrodes.
Ni/YSZ electrodes structures optimized for increased electrolysis performance and durability

Cermet Ni/YSZ electrodes are the most commonly applied fuel electrode for solid oxide cells (SOC) both when targeting solid oxide fuel cell (SOFC) applications and when used as solid oxide electrolysis cell (SOEC). In this work we report on the correlation between initial Ni/YSZ microstructure and the resulting electrochemical performance both initially and during long-term electrolysis testing at high current density and high p(H2O) inlet. Especially, this work focuses on microstructure optimization to hinder Ni mobility and migration during long-term operation and illustrates the key-role of electrode over-potential on the degradation of the Ni/YSZ electrodes in SOEC. We find that for long-term stability for electrolysis at high current densities and high p(H2O) the as-produced NiO/YSZ precursor electrode should be: 1) As dense as possible, 2) as fine particle and pore sized as possible and 3) the three phases (Ni, YSZ and pore phase) shall be size-matched and well-dispersed. Applying such microstructure optimized Ni/YSZ electrode we show SOEC test results with long-term degradation rate as low as 0.3-0.4%/kh at - 1 A/cm², 800 °C and inlet gas mixture of p(H2O)/p(H2):90/10. This enables SOEC operation of such cell for more than 5 years below thermo-neutral potential at these operating conditions.

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Relation between shape of Ni-particles and Ni migration in Ni-YSZ electrodes – a hypothesis

This is an attempt to explain a phenomenon of total depletion of Ni next to the electrolyte in Ni-YSZ cermet electrodes in solid oxide electrolysis cells during electrolysis at high current density/overpotential. Intuitively, we would think that Ni would always migrate down the steam partial pressure (pH2O) gradient as previously observed [1], but in the present cases Ni seems to migrate up the pH2O gradient. However, it is also observed that there is a preceding phase in this Ni-YSZ electrode degradation, namely that the Ni-particles closest to the YSZ electrolyte loose contact to each other. This means that the active three phase boundary (TPB) moves away from the electrolyte and causes a significant increase in the ohmic resistance as is also observed in electrochemical impedance spectra.

Study of variables for accelerating lifetime testing of SOFCs

Solid oxide fuel cell (SOFC) applications require lifetimes of several years on the system level. A big challenge is to proof/confirm/demonstrate such exceptionally long lifetimes. Accelerated or compressed testing are possible methods. Activities in this area have been carried out without arriving at a generally accepted result. First accelerated testing approaches were performed under non-steady operation conditions (current cycling, temperature cycling) by different researchers [1, 2]. However, cycling conditions seemed to have no significant impact on degradation mechanisms. Furthermore, tests done at different current load cycling profiles revealed a strong deviation between predicted and measured lifetime [3]. In this study, we present a detailed analysis of durability results for degradation mechanisms of single SOFC components as function of operating conditions. Electrochemical impedance data is collected and used to de-convolute the individual losses of single SOFC cell components – electrolyte, cathode and anode. The obtained knowledge is adopted to identify operation profiles and appropriate stresses in order to execute appropriate accelerated testing for lifetime investigation of SOFCs.
Elektrolyse gør al energi fra vindmøller værdifuld

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High performing SOFC via multilayer tape casting?

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Ni/YSZ microstructure optimization for long-term stability of solid oxide electrolysis cells
Sulfur Poisoning of Ni/stabilized-zirconia Anodes: Effect on Long-Term Durability

Triple phase boundary specific pathway analysis for quantitative characterization of solid oxide cell electrode microstructure

The density and percolation of Triple phase boundary sites are important quantities in analyzing microstructures of solid oxide fuel cell electrodes from tomography data. However, these measures do not provide descriptions of the quality of the TPB sites in terms of the length and radius of the pathways through which they can be reached. New methods for performing TPB specific pathway analysis on 3D image data are introduced, analyzing the pathway properties of each TPB site in the electrode structure. The methods seek to provide additional information beyond whether the TPB sites are percolating or not by also analyzing the pathway length to the TPB sites and the bottleneck radius of the pathway. We show how these methods can be utilized in quantifying and relating the TPB specific results to cell test data of an electrode reduction protocol study for Ni/Scandia-and-Yttria-doped-Zirconia (Ni/ScYSZ) anodes. A study of the TPB density and particle size distribution alone did not provide an explanation for the differences observed in electrode performance. However, the analysis of pathway lengths to the TPBs and the bottleneck radii to reach these TPB sites provided valuable microstructural insight that supported the findings from the electrochemical characterization of the Ni/ScYSZ anodes.
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Electrochemical characterization of $\text{La}_{0.6}\text{Ca}_{0.4}\text{Fe}_{0.8}\text{Ni}_{0.2}\text{O}_3$ cathode on $\text{Ce}_{0.8}\text{Gd}_{0.2}\text{O}_{1.9}$ electrolyte for IT-SOFC

For Solid Oxide Fuel Cells (SOFCs) to become an economically attractive energy conversion technology, suitable materials and structures which enable operation at lower temperatures, while retaining high cell performance, must be developed. Recently, the perovskitetype $\text{La}_{0.6}\text{Ca}_{0.4}\text{Fe}_{0.8}\text{Ni}_{0.2}\text{O}_3$ oxide has shown potential as an intermediate temperature SOFC cathode. An equivalent circuit describing the cathode polarization resistances was constructed from analyzing impedance spectra recorded at different temperatures in oxygen. A competitive electrode polarization resistance is reported for this oxygen electrode using a $\text{Ce}_{0.8}\text{Gd}_{0.2}\text{O}_{1.9}$ electrolyte, determined by impedance spectroscopy studies of symmetrical cells sintered at 800 _C and 1000 _C. Scanning electron microscopy (SEM) studies of the symmetrical cells revealed the absence of any reaction layer between cathode and electrolyte, and a porous electrode microstructure even when sintered at a temperature of only 800 _C. The performance of this cathode shows favorable oxygen reduction reaction (ORR) properties potentially making it an excellent choice for IT-SOFC application. © 2014, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.
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Ni/YSZ microstructure optimization for long-term stability of solid oxide electrolysis cells

In the last decade there has been a renewed and increased interest in electrolysis using solid oxide cells (SOC). So far the vast majority of results reported on long-term durability of solid oxide electrolysis cells (SOEC) have been obtained using SOC produced and optimized for fuel cell operation; i.e. solid oxide fuel cells (SOFC). However, previous long-term tests have shown that the stability behavior of the Ni/yttria-stabilized-zirconia (Ni/YSZ) fuel electrode may fall out quite differently depending on whether the cell is operated in fuel cell or electrolysis mode at otherwise similar test conditions. Initial work has shown significant microstructural changes of the Ni/YSZ electrode close to the electrolyte interface after long-term steam electrolysis test at -1 A/cm² at 800 °C. The results indicate that it will be advantageous to optimize the electrode structure with the aim of keeping the Ni particles in their required positions in the porous Ni/YSZ cermet close to the electrolyte. In this work we report cell tests and microstructures from reference and long-term tested SOEC with varied initial Ni/YSZ ratio with the aim of investigating the effect of changed Ni/YSZ ratio on long-term stability during steam electrolysis.

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Authors: Hauch, A. (Intern), Brodersen, K. (Intern), Karas, F. (Ekstern), Chen, M. (Intern)
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Sulfur Poisoning of SOFC Anodes: Effect of Overpotential on Long-Term Degradation

Sulfur impurities in carbon containing fuels for solid oxide fuel cells (SOFC), e.g. natural gas and biogas, typically lead to significant losses in performance due to the sulfur sensitivity of Ni/yttria-stabilized-zirconia (YSZ) anodes for SOFC. Full cells having Ni/YSZ anodes have been characterized during long-term galvanostatic operation in internal reforming gas mixture (CH4/H2O/H2:30/60/10), with 2 ppm H2S exposure to the anode for 500 hours at 850°C, at different current densities. This work focus on the long-term effect of H2S exposure over a few hundreds of hours; and describes and correlates the observed evolution of anode performance, over hundreds of hours, with sulfur exposure at low cell overpotential (low current density) and at high overpotential (high current density) with and without H2S exposure. For tests at low overpotential with H2S exposure only a reversible loss in performance was observed and post-mortem SEM analysis showed an intact Ni/YSZ anode microstructure. For tests at high cell overpotential the H2S exposure caused both a reversible loss in performance and an irreversible long-term degradation. Post-mortem SEM analysis of the Ni/YSZ anode from this tests showed increased porosity and lack of percolating Ni in the few microns of the anode closest to the anode/electrolyte interface.
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Sulfur_Poisoning_of_SOFC_Anodes.pdf
Electrochemical characterization of La$_{0.6}$Ca$_{0.4}$Fe$_{0.8}$Ni$_{0.2}$O$_{3-δ}$ perovskite cathode for IT-SOFC

Electrolyte supported symmetric cells featuring La$_{0.6}$Ca$_{0.4}$Fe$_{0.8}$Ni$_{0.2}$O$_{3-δ}$ (LCFN) electrodes are studied by electrochemical impedance spectroscopy. The aim is to describe the polarization losses of this mixed ionic electronic conductor electrode at various cell operating conditions for cells sintered at different temperatures. An equivalent circuit describing the cathode polarization resistances was constructed from analyzing impedance spectra recorded at different oxygen partial pressures and temperatures. Favorable oxygen reduction reaction properties are demonstrated for the LCFN cell sintered at 750°C with a polarization resistance of 0.05 Ω cm$^2$ at an operating temperature of 800°C in pure oxygen. © 2013 Elsevier B.V. All rights reserved.
Microstructural Degradation of Ni/YSZ Electrodes in Solid Oxide Electrolysis Cells under High Current

Niytria stabilized zirconia (YSZ) supported solid oxide electrolysis cells (SOECs) were exposed to long-term galvanostatic electrolysis tests, under different testing conditions (temperature, gas composition, current density etc.) with an emphasis on high current density (above $-1 \text{ A/cm}^2$). Detailed post-mortem characterizations were carried out to investigate microstructural changes after long-term galvanostatic tests, focusing on the Ni/YSZ electrode. Formation of ZrO$_2$ nano-particles on Ni surfaces was observed in cells exposed to $-1$ or $-1.5 \text{ A/cm}^2$ at 800 or 850°C, but not in those tested at current densities below $-0.75 \text{ A/cm}^2$. The formation of ZrO$_2$ nano-particles deteriorates Ni percolation and presumably decreases the number of active triple phase boundaries (TPBs) and is therefore considered a degradation phenomenon. It is hypothesized that the degradation of the Ni surface is a result of Ni-YSZ interfacial reactions, taking place under the conditions prevailing under strong polarization. A mechanism for the formation of ZrO$_2$ nano-particles on the Ni surface under the electrolysis cell testing is proposed and the possibility of Ni-YSZ interfacial reactions under such conditions (T, p(O$_2$)) is further elucidated by thermodynamic calculations.

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Scopus rating (2005): SJR 1.519 SNIP 1.484
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Microstructure characterisation of solid oxide electrolysis cells operated at high current density

High temperature solid oxide cells can be operated either as fuel cells or electrolysis cells for efficient power generation or production of hydrogen from steam or synthesis gas (H2 + CO) from steam and CO2 respectively. When operated under harsh conditions, they often exhibit microstructural degradation of cell components in relation to the loss of electrochemical performance specific to the mode of operation. Thus descriptive microstructure characterization methods are required in combination with electrochemical characterization methods to decipher degradation mechanisms.

In the present work, microstructure evolution of the Ni-yttria stabilized zirconia (YSZ) is followed as a function of galvanostatic steam electrolysis testing at current densities between -0.5 and -1.0 A cm-2 for periods of up to 750 hours at 800 °C. The volume fraction and size of the percolating Ni particles was statistically quantified using the mean linear intercept method as a function of current density and correlated to increases in serial resistance.

The above structural changes are then compared in terms of electrode degradation observed during the co-electrolysis of steam and CO2 at current densities up to -1.5 A cm-2. In this study, the formation of ZrO2 based nano particles at the Ni-pore interface is responsible for the loss of Ni-YSZ particle contact and thus loss of triple phase boundary. Formation of similar nano particles at Ni internal grain boundaries is also thought to be responsible for loss of Ni percolation.

Modeling degradation in SOEC impedance spectra

Solid oxide cell (SOC) performance is limited by various processes. One way to investigate these processes is by electrochemical impedance spectroscopy. In order to quantify and characterize the processes, an equivalent circuit can be used to model the SOC impedance spectra (IS). Unfortunately, the optimal equivalent circuit is often unknown and to complicate matters further, several processes contribute to the SOC impedance - making detailed process characterization difficult. In this work we analyze and model a series of IS measured during steam electrolysis operation of an SOC. During testing, degradation is only observed in the Ni/YSZ electrode and not in the electrolyte or the LSM/YSZ electrode. A batch fit of the differences between the IS shows that a modified Gerischer element provides a better fit to the Ni/YSZ electrode impedance than the frequently used RQ element - albeit neither equivalent circuit provides a perfect fit.

However, modeling with the Gerischer element indicates that the Ni/YSZ electrode performance decrease, relates to an electrochemical reaction resistance increase at the electrode triple phase boundaries. © 2013 The Electrochemical Society.
Optimizing solid oxide fuel cell cathode processing route for intermediate temperature operation

For Solid Oxide Fuel Cells (SOFCs) to become an economically attractive energy conversion technology suitable materials which allow operation at lower temperatures, while retaining cell performance, must be developed. At the same time, the cell components must be inexpensive - requiring both low-priced raw material and cost-effective production techniques. In this work the perovskite-type La0.6Ca0.4Fe0.8Ni0.2O3 (LCFN) oxide has been used in order to optimize intermediate temperature SOFC cathode processing route. The advantages this material presents arise from the low temperature powder calcination (∼600°C) and electrode sintering (∼800°C) of LCFN electrodes, making them a cheaper alternative to conventional SOFC cathodes. An electrode polarization resistance as low as 0.10Ωcm² at 800°C is reported, as determined by impedance spectroscopy studies of symmetrical cells sintered at a range of temperatures (800-1000°C). Scanning Electron Microscopy (SEM) studies revealed porous electrode microstructures, even when sintered at a temperature of just 800°C. The competitive performance of the electrodes sintered at low temperatures, combined with the low raw material cost, make these electrodes an excellent potential choice for SOFC cathodes. In this work a new cathode processing technique is presented which provides a more economical, lower temperature SOFC production route with no detrimental effect on device efficiency. © 2012 Elsevier Ltd.
Sulfur Poisoning of Ni/stabilized-zirconia Anodes – Effect on Long-Term Durability

Sulfur impurities in carbon containing fuels for solid oxide fuel cells (SOFC), e.g. natural gas and biogas, can lead to significant losses in performance due to the sulfur sensitivity of Ni/YSZ SOFC anodes. Full cells having Ni/YSZ and Ni/ScYSZ anodes have been characterized during long-term galvanostatic operation in internal reforming gas mixture (CH4/H2O/H2:30/60/10), with 2 ppm H2S exposure to the anode, at different current densities. The aim was not only to investigate the well-known initial performance drop associated with adsorbed sulfur in the Ni/stabilized-zirconia anodes, but also to focus on the long-term effect over a few hundred of hours. This work describes and correlates the observed evolution of anode performance, over hundreds of hours, with sulfur poisoning with the different operating conditions.

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Durable and Robust Solid Oxide Fuel Cells

The solid oxide fuel cell (SOFC) is an attractive technology for the generation of electricity with high efficiency and low emissions. Risø DTU (now DTU Energy Conversion) works closely together with Topsoe Fuel Cell A/S in their effort to bring competitive SOFC systems to the market. This 2-year project had as one of its' overarching goals to improve durability and robustness of the Danish solid oxide fuel cells. The project focus was on cells and cell components suitable for SOFC operation in the temperature range 600 – 750 °C. The cells developed and/or studied in this project are intended for use within the CHP (Combined Heat and Power) market segment with stationary power plants in the range 1 – 250 kWe in mind. Lowered operation temperature is considered a good way to improve the stack durability since corrosion of the interconnect plates in a stack is lifetime limiting at T > 750 °C. The fact that degradation and robustness is not very well explored or understood at operating temperatures below 750 °C, provides motivation for focussing on materials and cells suitable for, and operated in this temperature range.

A significant part of this project was concerned with improved understanding of degradation and failure mechanisms. Improved understanding of performance and lifetime limiting factors will make it possible to develop strategies for countering degradation and improving the power density of SOFC based systems, both necessary to advance towards the goals set out in the national plan for SOFC implementation.

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Multilayer tape cast SOFC – Effect of anode sintering temperature

Multilayer tape casting (MTC) is considered a promising, cost-efficient, up-scalable shaping process for production of planar anode supported solid oxide fuel cells (SOFC). Multilayer tape casting of the three layers comprising the half cell (anode support/active anode/electrolyte) can potentially be cost-efficient and simplify the half-cell manufacturing process. Fewer sintering steps (co-sintering), as well as fewer handling efforts, will be advantageous for up-scaled production. Previous reports have shown that our laboratory produces mechanically strong, high performing anode supported SOFC, with high reproducibility, by tape casting of the anode support [1]. Recent initial results obtained on SOFC with half-cells produced by successive tape casting (MTC) of anode support, anode and electrolyte layers, followed by cosintering of the half-cell, showed increased performance and stability upon FC operation compared to SOFC with half-cells produced by tape casting of anode support but spraying of active anode and electrolyte [2]. These results have initiated further work on MTC half cells. Initial MTC production results have shown that it is possible to co-sinter the MTC anode half cells in a rather large “temperature-window”. To increase our understanding of the MTC process, obtained microstructures and the resulting electrochemical performance of these SOFC, we here report a study of MTC based cells. The half-cells have been produced and co-sintered at 5 different temperatures from 1255 °C to 1335 °C. This study investigates the effect of the sintering temperature on the anode microstructure analysed via electron microscopy images; and correlate it with electrochemical performance of the anode obtained from full cell testing and analysed via iV-curves and impedance spectroscopy.

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Production of “Green Natural Gas” Using Solid Oxide Electrolysis Cells (SOEC): Status of Technology and Costs

This paper gives arguments in favour of using green natural gas (GNG) as storage media for the intermittent renewable energy sources. GNG is here defined as being CH₄, i.e. methane, often called synthetic natural gas or substitute natural gas (SNG), produced using renewable or at least CO₂ neutral energy sources only. Also dimethylether (DME = (CH₃)₂O), which might be called Liquefied Green Gas, LGG, in analogy to Liquefied Petroleum Gas, LPG, because DME has properties similar to LPG. It further gives a short review of the state of the art of electrolysis in general and SOEC in particular. Production of synthesis gas (H₂ + CO) from CO₂ and H₂O using SOEC technology is evaluated. GNG and LGG can be produced from synthesis gas (or short: syngas) by means of well established commercially available catalysis technology. Finally, estimations of costs and efficiencies are presented and the relative importance of cost and efficiency is briefly discussed.

General information
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Durability of Solid Oxide Cells
In recent years extended focus has been placed on monitoring and understanding degradation mechanisms in both solid oxide fuel cells and solid oxide electrolysis cells. The time-consuming nature of degradation experiments and the disparate conclusions from experiment reproductions indicates that not all degradation mechanisms are fully understood. Traditionally, cell degradation has been attributed to the materials, processing and cell operating conditions. More recently, focus has been placed on the effect of raw material and gas impurities and their long-term effect on cell degradation. Minor impurities have been found to play a significant role in degradation and in some cases can overshadow the cell operation condition related degradation phenomenon. In this review, several degradation diagnostic tools are discussed, a benchmark for a desirable degradation rate is proposed and degradation behaviour and mechanisms are discussed. For ease of navigation, the review is separated into the various cell components – fuel electrode, electrolyte and oxygen electrode. Finally, nano-particle impregnate stability is discussed.

Electrochemical characterisation of solid oxide cell electrodes for hydrogen production
Oxygen electrodes and steam electrodes are designed and tested to develop improved solid oxide electrolysis cells for H2 production with the cell support on the oxygen electrode. The electrode performance is evaluated by impedance spectroscopy testing of symmetric cells at open circuit voltage (OCV) in a one-atmosphere set-up. For the oxygen electrode, nano-structured La0.75Sr0.25MnO3 (LSM25) is impregnated into a LSM25/yttria stabilised zirconia (YSZ) composite, whereas for the steam electrode, nano-structured Ni and Ce0.8Gd0.2O2−δ (CGO) is impregnated into a Sr0.94Ti0.9Nb0.10O3−δ (STN) backbone. In the present study, the best performing oxygen electrode is a LSM25-YSZ composite with 20% porosity and impregnated with a LSM25 solution measuring a polarisation resistance (Rp) of 0.12 Ω.
cm² at 850 °C in oxygen. For the steam electrode, the best performance is obtained for a STN backbone, sintered at 1200 °C and impregnated with CGO/Ni, with an $R_p$ of 0.08 Ω cm² at 850 °C in 3% H₂O/H₂.

**General information**

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Electrolysis for Integration of Renewable Electricity and Routes towards Sustainable Fuels

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High performance anode supported SOFC produced by multilayer tape casting

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NiYSZ anode – Effect of pre-treatments on cell degradation and microstructures
Anode supported (NiYSZ–YSZ–LSM/YSZ) solid oxide fuel cells were tested and the degradation over hundreds of hours was monitored and analyzed by impedance spectroscopy. Test conditions were chosen to focus on the Ni/YSZ anode degradation and all tests were operated at 750°C, a current density of 0.75Acm−2. Oxygen was supplied to the cathode and the anode inlet gas mixture had a high pH2O/p(H2) ratio of 0.4/0.6. Commercially available gases were applied. The effect of different types of pre-treatments on the Ni/YSZ electrode degradation during subsequent fuel cell testing was investigated. Pre-treatments included operating at OCV (4% and 40% H2O in H2) prior to fuel cell testing, cleaning of the inlet H2 gas at 700°C and processing the anode half cell via multilayer tape casting. Analyses of impedance spectra
showed that the increase in the charge transfer reaction resistance in the Ni/YSZ (RNi,TPB) was decreased to \( \frac{1}{4} \) or less for the pre-treated and fuel cell tested cells when compared with a non-pre-treated reference tested cell, all operated at the same fuel cell test conditions. Scanning electron microscopy and image analyses for the non-pre-treated reference tested cell and selected pre-treated cells showed significant differences in the area fractions of percolating nickel both in the active anode and support layer.

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Web of Science (2010): Indexed yes
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Scopus rating (2009): SJR 2.117 SNIP 1.793
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.968 SNIP 1.726
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.597 SNIP 1.489
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.8 SNIP 2.224
Web of Science (2006): Indexed yes
Ni/YSZ electrode degradation studied by impedance spectroscopy — Effect of p(H_2O)

Anode supported solid oxide fuel cells have been tested and the degradation over time was monitored and analyzed by impedance spectroscopy. Reproducibility of initial cathode, anode and electrolyte performance was obtained. Anode (Ni/YSZ) degradation was analyzed for tests applying p(H_2O) of 0.2 atm, 0.4 atm and 0.6 atm at 750 °C and 0.75 A/cm². The anode degradation could be well described by the equation: RNi,TPB(t) = RNi,0 + ΔR∙(1 − exp(− t / τ)). The initial resistance and total increase for the Ni–YSZ charge transfer resistance, RNi,0 and ΔR, were similar for all tests (i.e. not directly correlated with p(H_2O)), but the characteristic time, τ, for the anode degradation was significantly higher for the test at p(H_2O) = 0.2 atm than at p(H_2O) of 0.4 atm and 0.6 atm.

General information
State: Published
Authors: Hauch, A. (Intern), Mogensen, M. B. (Intern), Hagen, A. (Intern)
Pages: 547-551
Publication date: 2011
Main Research Area: Technical/natural sciences

Publication information
Journal: Solid State Ionics
Volume: 192
Issue number: 1
ISSN (Print): 0167-2738
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.41 SJR 0.751 SNIP 0.88
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.819 SNIP 1.033 CiteScore 2.5
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.843 SNIP 1.304 CiteScore 2.62
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.902 SNIP 1.274 CiteScore 2.35
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.055 SNIP 1.258 CiteScore 2.31
A Composite Glass Seal for a Solid Oxide Electrolyser Cell Stack

General information
State: Published
Authors: Lönnroth, N. (Intern), Hauch, A. (Intern), Mogensen, M. B. (Intern), Chen, M. (Intern)
Publication date: 2010

Publication information
Patent number: EP2258014
Date: 08/12/2010
Original language: English
Fuel Cells and Hydrogen, Electrolysis

Bibliographical note
Patent:
No.: EP2104172
Complementary techniques for solid oxide electrolysis cell characterisation at the micro- and nano-scale

High-temperature steam electrolysis by solid oxide electrolysis cells (SOEC) is a method with great potential for transforming clean and renewable energy from non-fossil sources to synthetic fuels such as hydrogen, methane or dimethyl ether, which have been identified as promising alternative energy carriers. With the same technology, fuel gas can be used in a very efficient way to reconvert chemically stored energy into electrical energy, since SOECs also work in the reverse mode, operating as solid oxide fuel cells (SOFC). As solid oxide cells (SOC) perform at high-temperatures (700–900 °C), material degradation and evaporation can occur, e.g., from the cell-sealing material, leading to poisoning effects and aging mechanisms that decrease the cell efficiency and long-term durability. To investigate such cell degradation processes, thorough examination of SOCs often requires a chemical and structural characterisation at a microscopic and nanoscopic level. The combination of different microscopic techniques such as conventional scanning electron microscopy (SEM), electron probe microanalysis (EPMA) and the focused ion beam (FIB) preparation technique for transmission electron microscopy (TEM) allows for post-mortem analysis at a multi-scale level. These complementary techniques can be used to characterise structural and chemical changes over a large and representative sample area (micro-scale) as well as at the nano-scale level for selected sample details. This article presents a methodical approach for the structural and chemical characterisation of changes in aged cathode-supported electrolysis cells produced at Risø DTU, Denmark. Additionally, we present results from the characterisation of impurities at the electrolyte/hydrogen interface caused by evaporation of sealing material.

General information
State: Published
Organisations: Electrochemical Evaluation, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Electrochemistry, University of Fribourg, University of Freiburg
Authors: Wiedenmann, D. (Ekstern), Hauch, A. (Intern), Grobety, B. (Ekstern), Mogensen, M. B. (Intern), Vogt, U. (Ekstern)
Pages: 5053-5060
Publication date: 2010
Conference: 1st International Conference on Hydrogen Production, Oshawa (CA), 3-6 May, 01/01/2009
Main Research Area: Technical/natural sciences

Publication information
Volume: 35
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Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.74 SJR 1.142 SNIP 1.286
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.294 SNIP 1.319 CiteScore 3.46
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.212 SNIP 1.494 CiteScore 3.54
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.278 SNIP 1.467 CiteScore 3.38
ISI indexed (2013): ISI indexed yes
Ni/YSZ electrode degradation studied by impedance spectroscopy: Effects of gas cleaning and current density

Anode supported (Ni/YSZ–YSZ–LSM/YSZ) solid oxide fuel cells were tested and the degradation over time was monitored and analyzed by impedance spectroscopy. Test conditions were chosen to focus on the anode degradation and all tests were operated at 750 °C. O2 was supplied to the cathode and the anode inlet gas mixture had a high p(H2O)/p(H2) ratio of 0.4/0.6. Commercially available gasses were applied. Cells were tested over a few hundred hours applying varying current densities (OCV, 0.75 A/cm2 and 1 A/cm2). To investigate the effects of possible impurities in the inlet gas stream on the anode degradation, tests were set-up both with and without gas cleaning. Gas cleaning was done by passing the H2 over porous nickel at room temperature. It was found that cleaning of the inlet H2 gas more than halved the anode degradation under current load. For tests at OCV the increase in the Ni–YSZ charge transfer reaction resistance changed from 0.10 Ωcm2 to become negligible (below 0.002 Ωcm2) upon applying H2 gas cleaning over the couple of hundred of hours of testing. Both for tests with and without H2 gas cleaning applied, it was surprisingly found that operating the solid oxide fuel cells at OCV prior to fuel cell testing provided fuel cell tests with minimal/negligible anode degradation compared to tests where fuel cell testing was started immediately after initial characterization of the cells.

General information
State: Published
Authors: Hauch, A. (Intern), Mogensen, M. B. (Intern)
Pages: 745-753
Poisoning of Solid Oxide Electrolysis Cells by Impurities

Electrolysis of H2O, CO2, and co-electrolysis of H2O and CO2 was studied in Ni/yttria-stabilized zirconia (YSZ) electrode supported solid oxide electrolysis cells (SOECs) consisting of a Ni/YSZ support, a Ni/YSZ electrode layer, a YSZ electrolyte, and a lanthanum strontium manganite (LSM)/YSZ oxygen electrode. When applying the gases as received, the cells degraded significantly at the Ni/YSZ electrode, whereas only minor (and initial) degradation was observed for either the Ni/YSZ or LSM/YSZ electrode. Application of clean gases to the Ni/YSZ electrode resulted in operation without any long-term degradation, in fact some cells activated slightly. This shows that the durability of these SOECs is heavily influenced by impurities in the inlet gases. Cleaning the inlet gases to the Ni/YSZ electrode may be a solution for operating these Ni/YSZ-based SOECs without long-term degradation.

General information

State: Published
Authors: Ebbesen, S. (Intern), Graves, C. R. (Intern), Hauch, A. (Intern), Jensen, S. H. (Intern), Mogensen, M. B. (Intern)
Pages: B1419-B1429
Publication date: 2010
Main Research Area: Technical/natural sciences
Solid Oxide Electrolysis Cells: Degradation at High Current Densities

The degradation of Ni/yttria-stabilized zirconia (YSZ)-based solid oxide electrolysis cells operated at high current densities was studied. The degradation was examined at 850°C, at current densities of −1.0, −1.5, and −2.0 A/cm2, with a 50:50 (H2O:H2) gas supplied to the Ni/YSZ hydrogen electrode and oxygen supplied to the lanthanum, strontium manganite (LSM)/YSZ oxygen electrode. Electrode polarization resistance degradation is not directly related to the applied current density but rather a consequence of adsorbed impurities in the Ni/YSZ hydrogen electrode. However, the ohmic resistance degradation increases with applied current density. The ohmic resistance degradation is attributed to oxygen formation in the YSZ electrolyte grain boundaries near the oxygen electrode/electrolyte interface. ©2010 The Electrochemical Society
Advanced Test Method of Solid Oxide Cells in a Plug-Flow Setup

This paper describes a case study of two electrolysis tests of solid oxide cells [Ni/yttria-stabilized zirconia (YSZ)-YSZ-lanthanum strontium manganite (LSM)/YSZ] tested in a plug-flow setup. An extensively instrumented cell test setup was used, and the tests involved measurements of the cell impedance at open-circuit voltage and under current load, the cell voltage, and the in-plane voltage in the electrodes. From the cell-voltage measurements it was evident that a significant passivation of the cells occurred over the first similar to 10 days. Thereafter, the cells reactivated at constant electrolysis conditions. From measurements of the in-plane voltages in the electrodes and impedance spectra obtained during the electrolysis operation, we derive information about the resistance distributions in the Ni electrodes and describe how these distributions evolve over time. Impedance spectra at open-circuit voltage before and after electrolysis testing at various gas compositions were used to show that the Ni electrode was affected by the electrolysis operation, whereas the LSM electrode was not.

General information
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Electroceramics
Authors: Jensen, S. H. (Intern), Hauch, A. (Intern), Hendriksen, P. V. (Intern), Mogensen, M. B. (Intern)
Pages: B757-B764
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Journal: Electrochemical Society. Journal
Volume: 156
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Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.97 SJR 1.134 SNIP 0.867
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.037 SNIP 1 CiteScore 3.17
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.147 SNIP 1.206 CiteScore 3.36
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.151 SNIP 1.299 CiteScore 2.92
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.329 SNIP 1.296 CiteScore 2.61
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.33 SNIP 1.345 CiteScore 2.74
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
**Electrolysis of steam and CO₂**

**General information**
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy
Authors: Mogensen, M. B. (Intern), Jensen, S. H. (Intern), Ebbesen, S. (Intern), Hauch, A. (Intern)
Publication date: 2008
Event: Paper presented at Electroceramics XI, Manchester, United Kingdom.
Main Research Area: Technical/natural sciences

**FIB/TEM investigation of Si accumulation in the active layer of SOECs**

**General information**
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy
Authors: Soltmann, C. (Ekstern), Wiedenmann, D. (Ekstern), Hauch, A. (Intern), Vogt, U. (Ekstern), Mogensen, M. B. (Intern)
Publication date: 2008

**Host publication information**
Title of host publication: Proceedings (on CD-ROM)
Publisher: European solid oxide fuel cell forum
Main Research Area: Technical/natural sciences
Conference: 8th European Solid Oxide Fuel Cell Forum, Lucerne, Switzerland, 30/06/2008 - 30/06/2008
Source: orbit
Source-ID: 231635
Publication: Research › Article in proceedings – Annual report year: 2008

**Fremtidens energiforsyning**

**General information**
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Experimental Surface and Nanomaterials Physics, Department of Physics, Theoretical Atomic-scale Physics, Center for Nanoteknologi
Pages: 63-79
Publication date: 2008

**Host publication information**
Title of host publication: Nanoteknologiske horisonter
Place of publication: Lyngby
Publisher: Danmarks Tekniske Universitet (DTU)
Editor: Hansen, A.
Main Research Area: Technical/natural sciences
Highly efficient high temperature electrolysis

High temperature electrolysis of water and steam may provide an efficient, cost effective and environmentally friendly production of H-2. Using electricity produced from sustainable, non-fossil energy sources. To achieve cost competitive electrolysis cells that are both high performing i.e. minimum internal resistance of the cell, and long-term stable, it is critical to develop electrode materials that are optimal for steam electrolysis. In this article electrolysis cells for electrolysis of water or steam at temperatures above 200 degrees C for production of H-2 are reviewed. High temperature electrolysis is favourable from a thermodynamic point of view, because a part of the required energy can be supplied as thermal heat, and the activation barrier is lowered increasing the H-2 production rate. Only two types of cells operating at high temperature (above 200 degrees C) have been described in the literature, namely alkaline electrolysis cells (AEC) and solid oxide electrolysis cells (SOEC). In the present review emphasis is on state-of-the art electrode materials and development of new materials for SOECs. Based on the state-of-the-art performance for SOECs H-2 production by high temperature steam electrolysis using SOECs is competitive to H-2 production from fossil fuels at electricity prices below 0.02-0.03 is an element of per kWh. Though promising SOEC results on H-2 production have been reported a substantial R&D is still required to obtain inexpensive, high performing and long-term stable electrolysis cells.
Nanoscale chemical analysis and imaging of solid oxide cells
The performance of solid oxide cells (SOCs) is highly dependent on triple phase boundaries (TPBs). Therefore, detailed TPB characterization is crucial for their further development. We demonstrate that it is possible to prepare a similar to 50 nm thick transmission electron microscopy (TEM) lamella of the interface between the dense ceramic electrolyte and the porous metallic/ceramic hydrogen electrode of an SOC using focused ion beam milling. We show combined TEM/scanning TEM/energy-dispersive spectroscopy investigations of the nanostructure at the TPBs in a high-performance SOC. The chemical composition of nanoscale impurity phases at the TPBs has been obtained with a few nanometers lateral resolution. (c) 2008 The Electrochemical Society.
Solid Oxide Electrolysis Cells: Microstructure and Degradation of the Ni/Yttria-Stabilized Zirconia Electrode

Solid oxide fuel cells produced at Risø DTU have been tested as solid oxide electrolysis cells for steam electrolysis by applying an external voltage. Varying the sealing on the hydrogen electrode side of the setup verifies that the previously reported passivation over the first few hundred hours of electrolysis testing was an effect of the applied glass sealing. Degradation of the cells during long-term galvanostatic electrolysis testing [850°C, −1/2 A/cm², p(H₂O)/p(H₂)=0.5/0.5] was analyzed by impedance spectroscopy and the degradation was found mainly to be caused by increasing polarization resistance associated with the hydrogen electrode. A cell voltage degradation of 2%/1000 h was obtained. Postmortem analysis of cells tested at these conditions showed that the electrode microstructure could withstand at least 1300 h of electrolysis testing, however, impurities were found in the hydrogen electrode of tested solid oxide electrolysis cells. Electrolysis testing at high current density, high temperature, and a high partial pressure of steam [−2 A/cm², 950°C, p(H₂O)=0.9 atm] was observed to lead to significant microstructural changes at the hydrogen electrode-electrolyte interface.
A method to separate process contributions in impedance spectra by variation of test conditions

Many processes contribute to the overall impedance of an electrochemical cell, and these may be difficult to separate in the impedance spectrum. Here, we present an investigation of a solid oxide fuel cell based on differences in impedance spectra due to a change of operating parameters and present the result as the derivative of the impedance with respect to ln(f). The method is used to separate the anode and cathode contributions and to identify various types of processes.

General information
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Electroceramics, Physical Chemistry, Department of Chemistry
Authors: Jensen, S. H. (Intern), Hauch, A. (Intern), Hendriksen, P. V. (Intern), Mogensen, M. B. (Intern), Bonanos, N. (Intern), Jacobsen, T. (Intern)
Pages: B1325-B1330
Publication date: 2007
Main Research Area: Technical/natural sciences

Publication information
Journal: Electrochemical Society. Journal
Volume: 154
Issue number: 12
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Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.97 SJR 1.134 SNIP 0.867
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.037 SNIP 1 CiteScore 3.17
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.147 SNIP 1.206 CiteScore 3.36
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.151 SNIP 1.299 CiteScore 2.92
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.329 SNIP 1.296 CiteScore 2.61
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.33 SNIP 1.345 CiteScore 2.74
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.417 SNIP 1.312
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.45 SNIP 1.267
Durability of solid oxide electrolysis cells for hydrogen production

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Fuel Cells and Solid State Chemistry Division, Electrochemistry
Authors: Hauch, A. (Intern), Jensen, S. H. (Intern), Ebbesen, S. (Intern), Mogensen, M. B. (Intern)
Pages: 327-338
Publication date: 2007

Host publication information
Title of host publication: Energy solutions for sustainable development. Proceedings
Publisher: Risø National Laboratory
Editors: Sønderberg Petersen, L., Larsen, H.
ISBN (Print): 978-87-550-3603-1

Series: Denmark. Forskningscenter Risoe. Risoe-R
Number: 1608(EN)
ISSN: 0106-2840
Main Research Area: Technical/natural sciences
Risø-R-1608, Risø-R-1608(EN)

Electronic versions: 
Søren.pdf
DOIs: 10.1149/1.2790791
Links: http://dx.doi.org/10.1149/1.2790791

Bibliographical note
Copyright The Electrochemical Society, Inc. [2007]. All rights reserved. Except as provided under U.S. copyright law, this work may not be reproduced, resold, distributed, or modified without the express permission of The Electrochemical Society (ECS).
EM investigations of impurities in a fuel cell H2 electrode

General information
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Electroceramics
Authors: Hauch, A. (Intern), Jensen, S. H. (Intern), Kuhn, L. T. (Intern), Mogensen, M. B. (Intern)
Publication date: 2007
Event: Abstract from SCANNING 2007. 8. Annual international scientific meeting on scanning microscopies, Monterey, CA (US)
Main Research Area: Technical/natural sciences
Links:
Source: orbit
Source-ID: 216453
Publication: Research › Conference abstract for conference – Annual report year: 2007

How to transfer spectra from the INCA software to spectra that can be used in the NoranSystemSix software

General information
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy
Authors: Hauch, A. (Intern)
Publication date: 2007
Event: Paper presented at Thermo Fisher scientific microanalysis Nordic users meeting, Risø, Denmark.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 216673
Publication: Research › Paper – Annual report year: 2007

Nanoscale chemical analysis and imaging of solid oxide cells

General information
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy
Authors: Hauch, A. (Intern)
Publication date: 2007
Event: Paper presented at SERC biannual meeting, Risø, Denmark.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 216095
Publication: Research › Paper – Annual report year: 2007

Reversible solid oxide cells

General information
State: Published
Organisations: Electrochemistry, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy
Authors: Mogensen, M. B. (Intern), Jensen, S. (Intern), Hauch, A. (Intern), Chorkendorff, I. (Ekstern), Jacobsen, T. (Ekstern)
Publication date: 2007
Event: Paper presented at 32. International Cocoa Beach conference and exposition on advanced ceramics and composites, Cocoa Beach, FL (US)
Main Research Area: Technical/natural sciences
Links:
Reversible Solid Oxide Cells: Performance of Reversible Solid Oxide Cells: 301-MogensenPerformance of Reversible Solid Oxide Cells: A Review

Silica segregation in the Ni/YSZ electrode
Solid oxide fuel cells were tested as solid oxide electrolysis cells used for high-temperature steam electrolysis. The cells were tested at a variety of operation temperatures, current densities, and gas flows to the electrodes. The cell voltages monitored during the electrolysis operation increased significantly during the first few days of testing. Impedance spectroscopy obtained during electrolysis shows that it is the Ni/yttria-stabilized zirconia (YSZ) electrode that passivates. Reference cells and tested cells were examined in a scanning electron microscope after testing. These postmortem analyses reveal the reason for the observed passivation, because results from energy-dispersive spectroscopy clearly show evidence that silica-containing impurities have segregated to the hydrogen electrode/electrolyte interface during electrolysis testing. Examples of different microstructures and amounts of Si-containing impurities in the electrolyte/hydrogen electrode interface are presented and related to the electrolysis test conditions and the passivation histories of the electrolysis cells. (C) 2007 The Electrochemical Society.
Solid oxide electrolysis for fuel production

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Fuel Cells and Solid State Chemistry Division, Electrochemistry
Authors: Ebbesen, S. (Intern), Hauch, A. (Intern), Jensen, S. (Intern), Mogensen, M. B. (Intern)
Publication date: 2007
Main Research Area: Technical/natural sciences
Links:
http://www.risoe.dk/rispubl/reports/ris-r-1608_presentations.pdf
Source: orbit
Source-ID: 216300
Publication: Research › Conference abstract for conference – Annual report year: 2007

Performance and durability of solid oxide electrolysis cells
Solid oxide fuel cells produced at Risø National Laboratory have been tested as electrolysis cells by applying an external voltage. Results on initial performance and durability of such reversible solid oxide cells at temperatures from 750 to 950 degrees C and current densities from -0.25 A/cm(2) to -0.50 A/cm(2) are reported. The full cells have an initial area specific resistance as low as 0.27 Omega cm(2) for electrolysis operation at 850 degrees C. During galvanostatic long-term electrolysis tests, the cells were observed to passivate mainly during the first similar to 100 h of electrolysis. Cells that have been passivated during electrolysis tests can be partly activated again by operation in fuel cell mode or even at constant electrolysis conditions after several hundred hours of testing.

General information
State: Published
Organisations: Department of Chemistry, Ceramic processing, Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Electrochemistry
Authors: Hauch, A. (Intern), Jensen, S. H. (Intern), Ramousse, S. (Intern), Mogensen, M. B. (Intern)
Pages: A1741-A1747
Publication date: 2006
Main Research Area: Technical/natural sciences

Publication information
Journal: Electrochemical Society. Journal
Volume: 153
Issue number: 9
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BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.97 SJR 1.134 SNIP 0.867
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.037 SNIP 1 CiteScore 3.17
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.147 SNIP 1.206 CiteScore 3.36
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.151 SNIP 1.299 CiteScore 2.92
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.329 SNIP 1.296 CiteScore 2.61
Proton Diffusion in the Ni/YSZ Electrode of a Solid Oxide Cell

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Department of Physics, Department of Chemistry, Technical University of Denmark
Authors: Jensen, S. (Ekstern), Hauch, A. (Intern), Chorkendorff, I. (Intern), Jacobsen, T. (Intern), Mogensen, M. B. (Intern)
Pages: Abstract 843
Publication date: 2006
Main Research Area: Technical/natural sciences

Publication information
Journal: Electrochemical Society. Meeting Abstracts (Online)
ISSN (Print): 2151-2043
Original language: English
Electronic versions:
Jensen.pdf
Source: orbit
Source-ID: 264212
Publication: Research › peer-review › Conference abstract in journal – Annual report year: 2006

The potential of the solid oxide electrolyser for the production of synthetic fuels

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Authors: Jensen, S. (Ekstern), Hauch, A. (Intern), Mogensen, M. B. (Intern)
Publication date: 2006
Event: Abstract from Hypothesis 6, Havana (CU), 8-12 May, .
Main Research Area: Technical/natural sciences
Links:
Source: orbit
Source-ID: 309458
Publication: Research › Conference abstract for conference – Annual report year: 2006

Electrode stability in high temperature electrolysis of steam

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Authors: Hauch, A. (Intern), Jensen, S. (Ekstern), Mogensen, M. B. (Intern)
Publication date: 2005
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 308425
Publication: Research › Conference abstract for conference – Annual report year: 2005
**Ni/YSZ-electrode passivation at cathodic current**

**General information**
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Authors: Jensen, S. H. (Intern), Hauch, A. (Intern), Mogensen, M. B. (Intern)
Pages: 247-252
Publication date: 2005

**Host publication information**
Title of host publication: Solid state electrochemistry. Proceedings
Place of publication: Roskilde
Publisher: Risø National Laboratory
ISBN (Print): 87-550-3455-1
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 308383
Publication: Research › Article in proceedings – Annual report year: 2005

**Ni/YSZ electrodes in solid oxide electrolyser cells**

**General information**
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Authors: Hauch, A. (Intern), Jensen, S. H. (Intern), Mogensen, M. B. (Intern)
Pages: 203-208
Publication date: 2005

**Host publication information**
Title of host publication: Solid state electrochemistry. Proceedings
Place of publication: Roskilde
Publisher: Risø National Laboratory
ISBN (Print): 87-550-3455-1
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 308381
Publication: Research › Article in proceedings – Annual report year: 2005

**Stability of solid oxide electrolyser cells**

**General information**
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Authors: Hauch, A. (Intern), Jensen, S. (Ekstern), Menon, M. (Intern), Mogensen, M. B. (Intern)
Pages: 216-230
Publication date: 2005

**Host publication information**
Title of host publication: Technologies for sustainable energy development in the long term. Proceedings
Editors: Sønderberg Petersen, L., Larsen, H.
Series: Denmark. Forskningscenter Risoe. Risoe-R
Number: 1517(EN)
ISSN: 0106-2840
Main Research Area: Technical/natural sciences
2H chemical shift anisotropies from high-field 2H MAS NMR spectroscopy

2H chemical shift anisotropies (CSAs) have been determined for the first time for polycrystalline samples employing 2H MAS NMR spectroscopy at high magnetic field strength (14.1 T). The 2H CSA is reflected as distinct asymmetries in the manifold of spinning sidebands (ssbs) observed for the two overlapping single-quantum transitions. Least-squares fitting to the manifold of ssbs allows determination of the 2H CSA parameters along with the quadrupole coupling parameters. This is demonstrated for KD2PO4, ND4D2PO4, KD2O3, KDCO3, α-(COOD)2, α-(COOD)2 · 2D2O, and boehmite (AlO(OH)) which exhibit 2H shift anisotropies in the range 13 ≤ δσ ≤ 27 ppm. For fixed values of the shift anisotropy and the 2H quadrupole coupling it is shown that the precision of the CSA parameters depends strongly on the asymmetry parameter (ηQ) for the quadrupole coupling tensor, giving the highest precision for ηQ ≈ 0. The 2H CSA parameters (δσ and ησ) are in good agreement with 1H CSA data reported in the literature for the corresponding protonated samples from 1H NMR spectra employing various homonuclear decoupling techniques. The determination of 2H quadrupole coupling parameters and 2H (1H) CSAs from the same 2H MAS NMR experiment may be particularly useful in studies of hydrogen bonding since the 2H quadrupole coupling constant and the CSA appear to characterize bond lengths in a hydrogen bond in a different manner. © 2003 Elsevier Inc. All rights reserved.
Projects:

Modeling of degradation processes in high temperature electrolysis cells

Department of Energy Conversion and Storage
Period: 01/09/2016 → 31/08/2019
Number of participants: 4
Phd Student:
Trini, Martina (Intern)
Supervisor:
Hauch, Anne (Intern)
Hendriksen, Peter Vang (Intern)
Main Supervisor:
Chen, Ming (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

Development and pressure testing of solid oxide electrolyser cells

Department of Energy Conversion and Storage
Period: 01/07/2016 → 30/09/2016
Number of participants: 4
Phd Student:
Gao, Ying (Intern)
Supervisor:
Graves, Christopher R. (Intern)
Hauch, Anne (Intern)
Main Supervisor:
Jensen, Søren Højgaard (Intern)

Financing sources
SOFC degradation studies
Department of Energy Conversion and Storage
Period: 15/08/2015 → 14/08/2018
Number of participants: 3
Phd Student:
Ploner, Alexandra (Intern)
Supervisor:
Hauch, Anne (Intern)
Main Supervisor:
Hagen, Anke (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

Lifetime limiting effects in pre-commercial solid cell devices
Department of Energy Conversion and Storage
Period: 01/03/2014 → 21/06/2017
Number of participants: 7
Phd Student:
Skafte, Theis Løyre (Intern)
Supervisor:
Blennow Tullmar, Peter (Intern)
Graves, Christopher R. (Intern)
Main Supervisor:
Hjelm, Johan (Intern)
Examiner:
Hauch, Anne (Intern)
Lanzini, Andrea (Ekstern)
Weber, André (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

Elektrode Kinetics and Gas Conversion in Solid Oxide Cells
Department of Energy Conversion and Storage
Period: 01/01/2014 → 20/04/2016
Number of participants: 7
Phd Student:
Njodzefon, Jean-Claude (Intern)
Supervisor:
Graves, Christopher R. (Intern)
Weber, André (Ekstern)
Main Supervisor:
Hjelm, Johan (Intern)
Examiner:
Hauch, Anne (Intern)
Krügel, Albert (Ekstern)
Schefold, Josef (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Eksternt finansieret virksomhed

Relations
Publications:
Electrode Kinetics and Gas Conversion in Solid Oxide Cells
Project: PhD

In-situ Neutron Imaging of Solid Oxide Fuel Cells
Department of Energy Conversion and Storage
Period: 01/01/2013 → 20/04/2016
Number of participants: 7
Phd Student:
Makowska, Malgorzata Grazyna (Intern)
Supervisor:
Lauridsen, Erik Mejdal (Intern)
Strobl, Markus (Ekstern)
Main Supervisor:
Kuhn, Luise Theil (Intern)
Examiner:
Hauch, Anne (Intern)
Grünzweig, Christian (Ekstern)
Hall, Stephen A. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 FUU, 1/3 inst 1/3 Andet
Project: PhD

Forbedring af Materialer til fast Oxid Brændselsceller
Department of Chemistry
Period: 15/08/2004 → 28/01/2008
Number of participants: 7
Phd Student:
Hauch, Anne (Intern)
Supervisor:
Bilde-Sørensen, Jørgen (Intern)
Mogensen, Mogens Bjerg (Intern)
Main Supervisor:
Jacobsen, Torben (Intern)
Examiner:
Skaarup, Steen (Intern)
Falk, Lena K. L. (Ekstern)
Holtappels, Peter (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Risø (Løn)
Project: PhD

Activities:
The 66th Annual Meeting of the International Society of Electrochemistry
Anne Hauch (Participant)
Department of Energy Conversion and Storage
Applied Electrochemistry

**Description**
International Society of Electrochemistry 66th annual meeting

**Related event**
The 66th Annual Meeting of the International Society of Electrochemistry  
04/10/2015 → 09/10/2015  
Taipei, Taiwan, Province of China  
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

**Er der vedvarende energi nok til os alle?**  
Period: 21 Sep 2015 → 25 Sep 2015  
Anne Hauch (Lecturer)  
Department of Energy Conversion and Storage  
Applied Electrochemistry

**Related event**
Dansk Naturvidenskabsfestival 2015  
21/09/2015 → 25/09/2015  
Denmark  
Activity: Talks and presentations › Conference presentations

**Vedvarende energi: Ny teknologi, der ændrer vores hverdag**  
Period: 20 May 2015  
Anne Hauch (Lecturer)  
Department of Energy Conversion and Storage  
Applied Electrochemistry

**Description**
Foredrag om vedvarende energi og energikonvertering og lagring i forelæsningsserie om "Ny teknologi" på Aarhus Folkeuniversitet (Emdrup afd.)

**Unknown external organisation**
Activity: Talks and presentations › Conference presentations

**Energikonvertering - Brændselsteknologier og brynt: Vedvarende Energi**  
Period: 10 Feb 2015  
Anne Hauch (Lecturer)  
Department of Energy Conversion and Storage  
Applied Electrochemistry

**Description**
Foredrag om brændselsteknologier og bring i forelæsningsserien "Vedvarende Energi" på Aarhus Folkeuniversitet (Emdrup afdeling)

**Unknown external organisation**
Activity: Talks and presentations › Conference presentations

**Er der vedvarende energi nok til os alle?: Om brændselsteknologier og elektrolyseceller til effektiv energikonvertering**  
Period: 26 Sep 2014  
Anne Hauch (Lecturer)
Department of Energy Conversion and Storage
Applied Electrochemistry

**Description**
Foredrag i forbindelse med Dansk Naturvidenskabsfestival

Inviteret foredrag
Documents:
Brændselsceller Og Elektrolyseceller DanskNaturvidenskabsfestival AnneHauch September26th2014

**Related event**
Dansk Naturvidenskabsfestival
26/09/2014 → …
Lyngby, Denmark
Activity: Talks and presentations › Conference presentations

**European fuel cell 2014 - 11th European SOFC and SOE Forum 2014**
Period: 1 Jul 2014 → 4 Jul 2014
Anne Hauch (Speaker)
Department of Energy Conversion and Storage
Applied Electrochemistry

**Description**
"Ni/YSZ microstructure optimization for long-term stability of solid oxide electrolysis cells" (presentation)

**Related event**
European fuel cell 2014 - 11th European SOFC and SOE Forum 2014
01/07/2014 → 04/07/2014
Lucerne, Switzerland
Activity: Talks and presentations › Conference presentations

**13th International Symposium on Solid Oxide Fuel Cells (SOFC-XIII)**
Anne Hauch (Participant)
Applied Electrochemistry
Department of Energy Conversion and Storage

**Description**
Participation in and oral presentation at the 13th International Symposium on Solid Oxide Fuel cells (SOFC-XIII)

Sulfur Poisoning of Ni/stabilized-zirconia Anodes – Effect on Long-Term Durability

**Related event**
13th International Symposium on Solid Oxide Fuel Cells (SOFC-XIII)
06/10/2013 → 11/10/2013
Okinawa, Japan
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

**European Fuel Cell Forum 2012**
Period: 30 Jun 2012 → 3 Jul 2012
Anne Hauch (Participant)
Applied Electrochemistry
Department of Energy Conversion and Storage

**Description**
Deltager samt poster bidrag

Multilayer Tape Cast SOFC - Effect of Anode Sintering Temperature

Documents:
EFCF_poster_cbir_2012-06-22_hauc_edit_FINAL

Related event

European Fuel Cell Forum 2012
27/06/2012 → 29/06/2012
Luzern, Switzerland
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

Studienaevn DTU Energi (External organisation)
Period: 1 Jan 2012 → 31 Dec 2015
Anne Hauch (Chairman)
Department of Energy Conversion and Storage
Applied Electrochemistry
Description
Formand for DTU Energis studienævn
Body type: Institutstudienævn

Related external organisation

Studienaevn DTU Energi
Activity: Membership › Membership of committees, commissions, boards, councils, associations, organisations, or similar

UDTU Education in University Teaching at DTU
Anne Hauch (Participant)
Department of Energy Conversion and Storage
Applied Electrochemistry
Description
Participation in module 1-4 (all modules) in UDTU Education in University Teaching at DTU
UDTU - university teachers education

Related event

UDTU Education in University Teaching at DTU
02/08/2010 → 30/06/2011
Lyngby, Denmark
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.