World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:15, No:02, 2021

Detailed Degradation-Based Model for Solid Oxide Fuel Cells Long-Term Performance

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Abstract : Solid Oxide Fuel Cells (SOFCs) feature high electrical efficiency and generate substantial amounts of waste heat that make them suitable for integrated community energy systems (ICEs). By harvesting and distributing the waste heat through hot water pipelines, SOFCs can meet thermal demand of the communities. Therefore, they can replace traditional gas boilers and reduce greenhouse gas (GHG) emissions. Despite these advantages of SOFCs over competing power generation units, this technology has not been successfully commercialized in large-scale to replace traditional generators in ICEs. One reason is that SOFC performance deteriorates over long-term operation, which makes it difficult to find the proper sizing of the cells for a particular ICE system. In order to find the optimal sizing and operating conditions of SOFCs in a community, a proper knowledge of degradation mechanisms and effects of operating conditions on SOFCs long-time performance is required. The simplified SOFC models that exist in the current literature usually do not provide realistic results since they usually underestimate rate of performance drop by making too many assumptions or generalizations. In addition, some of these models have been obtained from experimental data by curve-fitting methods. Although these models are valid for the range of operating conditions in which experiments were conducted, they cannot be generalized to other conditions and so have limited use for most ICEs. In the present study, a general, detailed degradation-based model is proposed that predicts the performance of conventional SOFCs over a long period of time at different operating conditions. Conventional SOFCs are composed of Yttria Stabilized Zirconia (YSZ) as electrolyte, Ni-cermet anodes, and $LaSr_{1-x}Mn_xO_3$ (LSM) cathodes. The following degradation processes are considered in this model: oxidation and coarsening of nickel particles in the Ni-cermet anodes, changes in the pore radius in anode, electrolyte, and anode electrical conductivity degradation, and sulfur poisoning of the anode compartment. This model helps decision makers discover the optimal sizing and operation of the cells for a stable, efficient performance with the fewest assumptions. It is suitable for a wide variety of applications. Sulfur contamination of the anode compartment is an important cause of performance drop in cells supplied with hydrocarbon-based fuel sources. H_2S, which is often added to hydrocarbon fuels as an odorant, can diminish catalytic behavior of Ni-based anodes by lowering their electrochemical activity and hydrocarbon conversion properties. Therefore, the existing models in the literature for H_2-supplied SOFCs cannot be applied to hydrocarbon-fueled SOFCs as they only account for the electrochemical activity reduction. A regression model is developed in the current work for sulfur contamination of the SOFCs fed with hydrocarbon fuel sources. The model is developed as a function of current density and H_2S concentration in the fuel. To the best of authors' knowledge, it is the first model that accounts for impact of current density on sulfur poisoning of cells supplied with hydrocarbon-based fuels. Proposed model has wide validity over a range of parameters and is consistent across multiple studies by different independent groups. Simulations using the degradation-based model illustrated that SOFCs voltage drops significantly in the first 1500 hours of operation. After that, cells exhibit a slower degradation rate. The present analysis allowed us to discover the reason for various degradation rate values reported in literature for conventional SOFCs. In fact, the reason why literature reports very different degradation rates, is that literature is inconsistent in definition of how degradation rate is calculated. In the literature, the degradation rate has been calculated as the slope of voltage versus time plot with the unit of voltage drop percentage per 1000 hours operation. Due to the nonlinear profile of voltage over time, degradation rate magnitude depends on the magnitude of time steps selected to calculate the curve's slope. To avoid this issue, instantaneous rate of performance drop is used in the present work. According to a sensitivity analysis, the current density has the highest impact on degradation rate compared to other operating factors, while temperature and hydrogen partial pressure affect SOFCs performance less. The findings demonstrated that a cell running at lower current density performs better in long-term in terms of total average energy delivered per year, even though initially it generates less power than if it had a higher current density. This is because of the dominant and devastating impact of large current densities on the long-term performance of SOFCs, as explained by the model.

Keywords : degradation rate, long-term performance, optimal operation, solid oxide fuel cells, SOFCs
Conference Title : ICHEFC 2021 : International Conference on Hydrogen Energy and Fuel Cells
Conference Location : Amsterdam, Netherlands
Conference Dates : February 08-09, 2021