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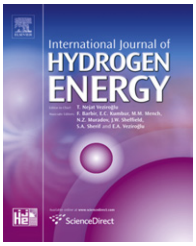

Review

Diagnosis methodology and technique for solid oxide fuel cells: A review

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ABSTRACT

The present study aims to identify and recollect the articles existing in literature that deal malfunction or failure causes of SOFC cells and relative diagnostic systems. This work is motivated by the increasing demand for diagnostic techniques aimed at both increasing durability and fully exploiting SOFC benefits throughout system lifetime. This paper reviews SOFC cells degradation phenomena and relevant fault detection methodologies already available, having found a gap in literature, above all relative to SOFC electrode microstructural degradation related, specifically, to sintering of the electrode microstructure, poisoning of the cathode microstructure with chromium products outgassed from the interconnect plates, carbon deposition in the anode, anode sulfur poisoning and boron SOFC cathodes' poisoning. It is therefore encouraged a future effort of the research activity in this specific sector.

Instead, relative to the degradation phenomena that cause increase in Ohmic resistance, different papers already available in the technical literature have been presented and discussed, as mentioned in Sections 3 and 4. On the basis of the analysis results, it has been possible to identify specific parameters (or at least analysis methodologies to obtain them) that can be implemented in diagnostic systems for the detection of particular failure modes of such a typology.

1. Introduction

Today electrical power is provided mainly by conventional power generation technologies that rely on fossil fuel combustion, which contributes to both global warming and local air pollution. For this reason clean energy systems must be developed quickly, thus allowing the change from a fossil fuel-based economy to a new sustainable economy.

The fuel cell is an emerging alternative to traditional power generation systems; it offers the potential for higher electrical efficiencies and lower emissions.

Solid oxide fuel cells (SOFCs) are considered an alternative to replace fossil fuel combustion in power generation. The SOFCs operate in the 600–1000 °C range which makes possible to combine them with other conventional thermal cycles to obtain thermal efficiency increase. Capable of generating electricity with relatively high efficiency, SOFCs are especially suitable for stationary electricity generation. Noise and vibration levels associated with mechanical motion during operation are very low; it makes possible to install the system in urban areas. Moreover the size of a SOFC module is flexible, allowing its use in any power range up to megawatts.

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Nomenclature

a	radius of a delamination in the center of the cell
AE	acoustic emission
DC	direct current
E_{AE}	energy of the AE signal
FEA	finite elements analysis
GDC	gadolinium doped ceria
HT-SOFC	high-temperature SOFC
IT-SOFC	intermediate temperature solid oxide fuel cell
K_B	Boltzmann constant
L	radius of a circular cell
LSCF	lanthanum strontium cobalt ferrite
LSM	strontium-doped lanthanum manganite
PEN	positive electrode–electrolyte–negative
$p_{O_2}^{anode}$	oxygen partial pressure of the anode
$p_{O_2}^{eq}$	Ni/NiO equilibrium pressure of the anode
$p_{O_2}^{I}$	oxygen partial pressure at the cathode
$p_{O_2}^{c}$	oxygen pressure inside the electrolyte just inside the cathode/electrolyte interface
P_s	survival probability
$\bar{R}_s$	normalized series resistance
R_s^0	series resistance prior to degradation
$\bar{R}_p$	normalized polarization resistance
R_p^0	polarization resistance prior to degradation
SOFC	solid oxide fuel cell
t	thickness of the delamination of the cell
TPoF	total probability of failure
V_j	volume of the jth layer
YSZ	yttria-doped zirconia
$\mu_{O_2}^{I}$	chemical potential of oxygen in the gas phases at the cathode
$\mu_{O_2}^{membrane}$	chemical potential of oxygen in the membrane
$\mu_{O_2}^{o}$	standard state gas phase oxygen chemical potential
σ_r	tensile radial stress

Despite their positive characteristics, SOFCs have not reached commercial status, due to problems related to durability, reliability and cost. The importance of these first two problems (i.e. durability and reliability) is reflected in the significant research efforts, within the SOFC community, aiming to investigate the degradation mechanisms affecting SOFC systems and the related prediction/diagnosis tools.

The total degradation of the stack performance generally can be originated from deterioration of single components as well as from mutual interactions among the cell components. Moreover, the severe environmental operative conditions of SOFC limit the choice of suitable materials and pose important challenges to the stability of the different cell components [1].

Thermo-mechanical issues, such as electrode delamination and electrolyte cracking, and thermo-chemical phenomena, such as anode reoxidation, oxide layer growth, electrode poisoning and microstructure coarsening, can be identified [2–6]. The nature of these mechanisms is varied, as well as their potential corrective actions. Some of these degradation mechanisms are reversible, such as early stage carbon deposition or sulfur poisoning [7], whereas others are irreversible, for example electrode delamination [5,6,8,9] and electrolyte cracking. Although they are different in nature, the effect on cell performance in long-term degradation testing is common to all of them: a loss in the available potential at constant current load. In other words, it is not possible to identify a specific degradation mechanism or combination of mechanisms only by observing changes to the DC potential of the cell at constant current. For this reason, the need to develop a diagnostic technique that allows the identification of a specific degradation mechanism of SOFCs in a minimally invasive way, is felt. If reversible degradation occurs, the method would indicate the possibility to correct the failure while the fuel cell is in operation. In the case of irreversible degradation, the method would aid in identifying the specific cause of failure of a component that needs replacement, so that operating conditions cell or stack materials or designs could potentially be adjusted in subsequent tests to minimize further degradation.

As already indicated great efforts have been made worldwide in analyzing SOFC degradation mechanisms, but resulting in a fragmentary scenario. For this reason the object of the present work is a thorough analysis on the various degradation mechanisms that can occur within a SOFC and their different detection methodologies already described in literature. In particular, the analysis of the diagnosis procedures aims to highlight possible gaps, referring to which it is evident the scientific interest on the development of dedicated research activities.

Therefore, it has been tried to analyze, in detail, the numerous causes of SOFC failure and to identify, for each fault mode, the available methods of detection.

In particular, the first part of this work, Section 2, provides some generalities about SOFC fundamentals with a specific attention to chemical reactions occurring at the anode and cathode side. In Section 3, the main degradation causes have been taken to account, while in Section 4 diagnosis systems and procedures already presented in the literature have been analyzed, focusing on the positive effects and relevance relative to the critical issues about SOFC reliability. Finally, in the technical literature a lack has been observed in reference to the failure detection related to microstructural degradation, while many studied are available about faults that lead to increase in cell Ohmic resistance, such as delamination, SOFC seals rib detachment and thermal stress.

2. SOFC fundamentals

Solid oxide fuel cells offer great promise to generate energy from hydrocarbons. They convert the fuel chemical energy directly into electrical energy through electrochemical