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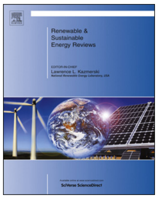

A review on the selection of anode materials for solid-oxide fuel cells

Shabana P.S. Shaikh*, Andanastuti Muchtar, Mahendra R. Somalu

Fuel Cell Institute, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia

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ABSTRACT

Solid-oxide fuel cells (SOFCs) are the most widely used fuel cells because they exhibit flexibility, power generation efficiency, and low pollution formation. Research on SOFC anodes is a major and challenging task in the field of SOFCs. This review highlights the anode materials that may be used for SOFC applications. The use of cermet-based oxide materials as anodes for SOFCs is also discussed in detail. A literature survey conducted over the last 10 years shows that increased power generation efficiency may be attributed to anode materials used in such cells. Oxide-based anode materials with perovskite and several oxides with cubic fluorite structures are further described. Based on the review conducted, we find that cubic fluorite-structured compounds are the most promising anode materials reported thus far. Analyses of the structure and electrical performance of anode materials show as well that copper–gadolinium-doped cerium oxide (Cu–GDC) cubic fluorite-structured anodes exhibit higher electronic conductivity potential than yttria-stabilized zirconia-based anode materials.

Contents

1. Introduction

Solid-oxide fuel cells (SOFCs) are the most widely used alternative energy sources and power-generating devices that are expected to yield highly efficient energy using hydrocarbon and fossil fuels. SOFC technology is used to produce electricity with negligible amounts of pollution and is thus an environment-friendly energy-conversion method of producing electrical energy with a high efficiency of approximately 60% [1].

Currently, many scientists, researchers, and engineers around the globe are showing keen interest in commercializing fuel cell technology. Thus, one of the most popular and innovative sources of renewable energy for the future is the hydrogen economy. The regenerative fuel cell might be the answer that hydrogen economists are looking for. It produces an electrical current through an electrochemical reaction between hydrogen and oxygen at a porous electrode (anode and cathode) interface, by completing an electrical circuit with the emission of the harmless byproduct, water. Unlike a battery, SOFCs more efficiently generate electricity up to 100 kW, compared with other types of fuel cells through the internal reforming process, as long as the fuel is provided to the electrode externally. SOFC can work at intermediate as well as high temperatures within the range of 700–1000 °C with 60% efficiency [2].

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* Corresponding author. Tel.: +603 89118534; fax: +603 89118035.
E-mail address: shabanamsrl@gmail.com (S.P.S. Shaikh).

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At such high temperatures, there is no need for a separate reformer to extract the hydrogen from the fuel in SOFC technology. Since SOFC can be used as a cogeneration system for home use, the major issue for commercialization is to balance the reliability and durability with a low cost.

Globally, many researchers are studying to commercialize SOFC to solve the energy problem in near future, as high temperature SOFCs showed high efficiency. During the literature survey, a few case studies were observed for SOFC technology as follows:

1. Tokyo Gas worked to develop cell stack performance to its maximum possible extent in order to prepare for the early stage of the commercialization of SOFC[3].
2. Fuel Cell Energy developed a direct fuel cell of 250 kW products in corporation by launching its first commercial unit in 2003, which was already operating at more than 50 stations. These units are now operating at more than 50 services worldwide [4].
3. Wellington states that the fuel cell, which received financial backing from Global Energy's (GE's) Ecomagination program, could generate electricity at any location with a supply of natural gas. It could start up quickly, did not need new transmission lines, and produced lower emissions than conventional power plants [5].

The high temperature SOFC showed tremendous promise, with high efficiency and low pollution, for a wide range of applications. Now, SOFCs are in demand as they are very clean and pollution free with a high efficacy of 60–65%, and a low cost compared with solar and wind energy. The fuel cell can be used to generate energy for small to medium scale stationary appliances, and is tolerant to carbon monoxide and sulfur impurities.

The advantages above validate the interest for the fuel cell in high as well as intermediate temperature as the next generation of electric and thermal products. However, due to its high cost, it is difficult to commercialize in many applications such as residential, industrial, transportation, and stationary. Recently, many scientists have used stainless steel in place of platinum, as a rare metal like platinum is very expensive. As a result, fuel cell technology is difficult to commercialize. Thus, there is need to search for economical friendly and alternative anode materials that can act as a catalyst in SOFCs [6]. SOFCs consist of three major layers that are composed of ceramic materials such as cathodes, electrolytes, and anodes. The electrolyte is a dense layer of ceramic oxide material, and anode/cathodes are both porous electrodes. It is urgent to confirm the high durability, reliability, and low cost of SOFCs for commercialization. Therefore, in this review, the authors attempted to identify issues regarding the confirmation of reliability of SOFCs through various evaluating parameters, fundamental properties, and advanced synthesis techniques for different anode materials for SOFC, to commercialize it at an early stage by reducing its manufacturing cost.

Compared with solar cells and wind energy, SOFCs are a cheaper, durable, and reliable source of energy. In addition, SOFCs emit negligible amounts of greenhouse gases, which reduce pollution and improve the environment. According to the literature survey, it was observed that in the last few years, the cost of the fuel cell unit declined from approximately $8000/kW in 2004 to $4800/kW in 2006. Still, globally, many scientists and researchers are attempting to further reduce the manufacturing cost of the SOFC unit by searching for new electrode materials and low cost synthesis techniques. Thus, it was observed that SOFCs have a key disadvantage of high cost. As a result, it is the main objective of researchers to minimize the manufacturing cost by selecting economical synthesis techniques and suitable alternative catalytic anode materials, which can work at lower as well as intermediate temperatures.

A number of companies such as Acumentrics, General Electric, Ion America, Rolls Royce, and Siemens Power Corp. are trying to lower the cost to commercialize SOFCs by developing new anode and cathode materials for the SOFC stack. From this review it is observed that, SOFC techniques might be needed $0.024/kW for the operation and its maintenance with production cost of $2850/kW. According to Fuel Cell Energy (FCE) of Danbury, Connecticut, additional hydrogen can be produced within the fuel cell stack, in which hydrogen and electricity can be coproduced using methane or natural gas as a fuel at the anode site. With reference to Table 1 [7], few companies believes that they could offer a 50% reduction in operating cost compared with the more conventional unit, using a novel electro-chemical hydrogen separation unit with 68% of hydrogen production efficiency [3], so that hydrogen can be used in transportation and industrial applications [3].

According to a survey conducted by Bloom Energy Fuel Cells, the solar cell has a number of major disadvantages; the cost of solar cell is very high compared with SOFCs, and solar energy can only generate electricity during the daytime. Weather can also affect the efficiency of solar energy, and the pollution produced is higher compared with SOFCs [8]. Table 2 shows the advantage and disadvantages of solar energy, wind energy and Fuel Cell Energy techniques [3,9,10].

Several researchers have improved the performance of intermediate-temperature SOFCs (IT-SOFCs) by enhancing the structural, mechanical, and electrical properties of the electrode/electrolyte interface in anode symmetric cells. Previous studies published over the last 10 years have described anodes, where fuel oxidation takes place, as basic components of SOFCs. Selecting the appropriate anode materials is significant to improving the electronic conductivity of single cells in IT-SOFCs.

An anode is a charged porous electrode in an electrical circuit. This electrode functions as an actively charged pole that facilitates

Table 1
Estimated cost of hydrogen production by different methods.

Sources for hydrogen production	Hydrogen production method	Hydrogen production cost
Natural gas SOFC	Internal steam reforming method	$1.47 per kg
Biomass(Syngas)	Thermo chemical and bio chemical process	$5–7 per kg
Coal	Gasification process	$2.00–2.50 per kg
Water	Electrolysis method	$6–7 per kg
methanol	Steam methane reforming	$2–5/kg [Ref]
Distributed wind	Electrolysis	$7.26 per kg

*References are mentioned in main text. Cost will be varying with respect to synthesis technique.