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Current developments in reversible solid oxide fuel cells

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Solid Oxide Fuel Cells (SOFC) and Solid Oxide Electrolyte Cells (SOEC) are often considered precluded mainly by their high cost, even when several technical issues have been continuously tackled over the past decades. Our energetic matrix is essentially based on finite fuel sources, which involve the emission of environmentally hazardous pollutants. Nevertheless, now there are several feasible and profitable benign routes for energy generation through solid oxide cells development, mainly for cells capable to produce energy and store it employing hydrogen as energy carrier. Those cells act reversibly as fuel or electrolyzer systems, which may be integrated in hybrid renewable energy plants and may be referred to as Reversible Solid Oxide Fuel Cells (RSOFC). In this article, the operation principles of SOEC and SOFC and the current state of the electrolyte, fuel and oxygen electrodes has been reviewed and discussed in detail. Each major section is divided into materials families, including manufacturing issues. Novel materials and processing techniques are currently in development and are summarized here. Moreover, key-points are suggested to overcome the known drawbacks and to improve the performance and economic feasibility in order to enhance the commercialization of RSOFC technology.

Contents

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1. Introduction

Problems related to greenhouse gas emissions, energy supplies and their costs, such as dwindling fossil fuel reserves, human and environmental diseases and climate change are strong arguments to shift towards a more environmentally benign fuel matrix based in renewable energy [1–4]. Finite fuel sources like coal, petrol and natural gas are the major energy suppliers, but the demand rate grows faster than the energy generation threatening the energy balance. Alternatively, the use of standalone or hybrid renewable energy systems can help meeting the future demand [5–9].

Renewable energy produces a varying supply of power. Demand for electrical power also varies continuously, encouraging energy storage to match supply and demand. Two approaches are normally used: batteries or a coupled fuel cell-electrolyzer with hydrogen as energy carrier [10–13]. This review is focused on reversible solid oxide fuel cells (RSOFC), which operate in both fuel cell and electrolysis modes, fulfilling both requirements in a single device.

Key issues such as operation principles, processing parameters and performance evaluation of RSOFC systems are included. First, a brief presentation is given including technical viability, thermodynamic fundamentals and current status of RSOFC. Then, a section for each main component (electrolyte, fuel electrode and oxygen electrode) is presented. Throughout the manuscript major research results and challenges in reversible solid oxide fuel cells are summarized.

1.1. Role and viability in renewable energy

Among fuel cells, solid oxide fuel cells (SOFC) are the most efficient (> 60%) for conversion of hydrogen directly into electrical power, and one of the cleanest routes to produce electricity due to their low greenhouse emissions [14–16]. Solid oxide electrolyzer cells (SOEC) correspond to the reverse operation of SOFC, which are also the most efficient comparing to low temperature electrolyzer as alkaline and polymer electrolyte membrane (PEM) cells. Alkaline water electrolyzer show efficiencies exceeding 80% and PEM may reach 83.4%; in comparison, efficiencies around 98% are reported for SOEC operating at 650 °C [17,18]. Likewise, high temperature electrolysis is more feasible than their lower temperature counterparts PEM and alkaline technologies (≈ 66% lower cost) [19,20].

The ideal configuration to produce electricity from renewable energy systems depends on the environment and equipment issues. Thus, the final energy costs may vary in a broad range (0.149–1.104 US$/kWh) [21]. Comparative designs show that renewable energy systems are currently less cost intensive in specific conditions (e.g. 0.438 vs. 0.510 US$/kWh for solar-wind-diesel and diesel systems, respectively) . The payback time of hybrid wind turbine and hybrid photovoltaic panel systems is approximately 3–4 years and 6–7 years, respectively. For hydrogen use, the payback takes more time (up to 25 years), because of the high initial investment in the fuel cell, the electrolyzer and the hydrogen tank [11]. However, a RSOFC can perform the fuel cell/electrolyzer work in a single device, employing the available surplus of cheap off-peak energy from renewable sources for hydrogen production by electrolysis and using it to generate electricity with decreasing costs [21–23]. An economic analysis in a 1-year period, considering a RSOFC working 2920 h in SOEC mode and 2815.2 h in SOFC mode for a hybrid photovoltaic system found a comparatively low electricity cost of 0.068 US$/kWh [23].

Alternatives as synthetic fuel production using co-electrolysis based cycles, can be competitive with gasoline at ≈ 2 US$/gal (0.53 US$/L), producing the fuel with electricity below 0.03 US $/kWh from a constant power supply [20]. The efficiency conversion electricity/fuel of these systems can be high as 70%; however, intermittent operation requires additional technological development to reduce initial capital cost [20,24].

From the industrial standpoint, SOEC-cells coupled with catalytic synthesis for fuel production could become the key enabling technology for upcoming sustainable energy scenarios, whilst SOFC commercialization is still some years away under the current market conditions [25,26]. In the future, reductions in the prices of renewable energy components are expected, making the corresponding technology economically feasible. The benefits derived from these systems are continuous operation and low pollution levels. Although several issues have been solved, some drawbacks discussed through the manuscript are still associated to solid oxide cells. Reliability, new materials, performance, stability and reduced production costs are the main concerns for RSOFC research and development.

1.2. Operating principles and thermodynamics

As previously described, a RSOFC is a high temperature device able to operate as fuel cell (SOFC) and electrolyzer (SOEC). In SOFC mode, it can generate electricity and heat by electrochemical combination with air of a fuel such as H_2, natural gas, hydrocarbons or syngas. In SOEC mode coupled with a power source, it produces chemical energy by electrolysis of H_2O, CO_2 or CO_2+H_2O [16,27,28]. Fig. 1 illustrates the operating principles of the RSOFC.

In RSOFC, the electrode reactions depend on the stream feedstock. For water and hydrogen, the reactions at the fuel electrode and oxygen electrode are Eq. (1) and Eq. (2), respectively, which may be combined into an overall reaction Eq. (3). In this case, where the SOEC mode corresponds to the reactions carried out from left to right, and SOFC mode to the opposite way:

$$H_2O + 2e^- \rightleftharpoons O^{2-} + H_2 \tag{1}$$

$$O^{-2} \rightleftharpoons \frac{1}{2} O_2 + 2e^- \tag{2}$$

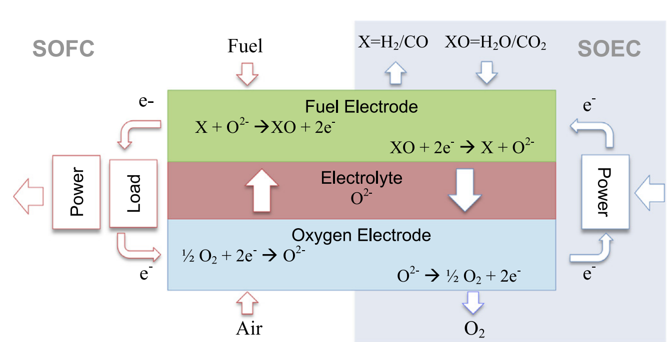

Fig. 1. Operating RSOFC principles: SOFC and SOEC modes.