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Thermodynamic and electrochemical analyses of a solid oxide electrolyzer for hydrogen production

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ABSTRACT

In this paper, a modeling of the Solid Oxide Electrolysis Cell (SOEC), through energetic, exergetic and electrochemical modeling approaches, is conducted, and its performance, particularly through exergy efficiency, is analyzed under various operating conditions and state properties for optimum hydrogen production. In a comprehensively performed parametric study, at a single electrolysis cell scale, the effects of varying some operating conditions, such as temperature, pressure, steam molar fraction and the current density on the cell potential and hence the performance are investigated. In addition, at the electrolyzer system scale, the overall electrolyzer performance is investigated through energy and exergy efficiencies, in addition to the system's power density consumption, hydrogen production rate, heat exchange rates and exergy destruction parameters. The present results show that the overall solid oxide electrolyzer energy efficiency is 53%, while the exergy efficiency is 60%. The exergy destruction at a reduced operating temperature increases significantly. This may be overcome by the integration of this system with a source of steam production.

Introduction

The environmental challenge, which has been created as a result of increasing fossil fuel consumption and the subsequent carbon emission, mandates a significant attention not only to the economic cost of the current energy resources but also to the environmental consequences of using these resources. Renewable energy resources, such as solar, wind, and geothermal energy, are considered the most promising options to replace the finite fossil fuel resources; however, among the major limitations of these resources is that they are intermittent and site-dependent. This limitation reduces the commerciality of these resources. Therefore, storage is required to reduce the mismatch between energy production and demand and also to facilitate subsequent transportation of this energy. Several energy storage options, such as pumped hydro, flywheel, compressed air, capacitors, and batteries have been proposed to offset such a mismatch between energy production and demand which persists in renewable resources. However, the success of any storage option depends on a number of factors, including type of application, long-term performance, environmental impact, and cost

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competitiveness. Using hydrogen as a storage mechanism and carbon-free energy carrier, recently has been pursued as a promising storage alternative that can serve a wide-range of applications. Electrolyzers demonstrated reliable performance with minimum environmental impact. In addition, hydrogen can be distributed as an essential commodity of many modern chemical processes such as ammonia synthesis, plastic and metal manufacturing, oil refineries and food industries. Such processes, according to the International Energy Agency (IEA), consumes about 65 million tons of hydrogen annually [1]. Therefore, the interest in hydrogen production is expected to drastically grow in the near future with a remarkable focus on non-conventional environmentally friendly technologies such as electrolysis [2,3].

Electrolysis technology is an electrochemical technology uses electricity to split water into oxygen and hydrogen. In contrast to conventional hydrogen production methods that require hydrocarbons as a feedstock such as steam methane reforming (SMR), partial oxidation, and coal gasification. Thus they emit substantial amounts of carbon dioxide and other pollutants into the atmosphere. Electrolysis process can be carbon-free technology and environmentally friendly if electricity is exclusively supplied by renewable resources. At present, only about 4% of the total world hydrogen consumption is produced from electrolysis systems while about 96% is produced from the aforementioned conventional fossil-based technologies [4].

The concept of hydrogen production using renewable electricity resources has been proposed and investigated in a number of research studies [5–8]. In these studies, low temperature electrolyzers (70–100 °C) are used to convert electricity to hydrogen with efficiencies in the range of 56–70% [9]. For example, the solar photovoltaic (PV) based low-temperature electrolyzers are estimated to achieve up to 13%, based on utilizing a 19% efficient PV system coupled with 70% efficient electrolyzer. Two low temperature electrolysis technologies are considered mature and commercially available which are alkaline and proton exchange membrane (PEM) electrolyzers. Alkaline electrolyzers use aqueous solutions such as potassium hydroxide (KOH) as an electrolyte while the electrodes are made of nickel-plated steel for anode and steel for the cathode. Alkaline electrolyzers are used in many industrial applications due to their improved durability and cost competitiveness. On the other hand, PEM electrolyzers are fabricated of proton conductive polymer electrolytes and two electrodes contain precious metal catalysts such as platinum.

However, the interest in high temperature solid oxide electrolyzers (SOE), compared with low temperature electrolyzers, is driven by the higher conversion efficiency and lower electricity consumption that high temperature electrolyzers have compared with low ones. In 1991, Arashi et al. [10] estimated that the efficiency of concentrated solar hydrogen production to be in the range of 20–28%. Therefore, a number of researchers have investigated integrating high temperature solid oxide electrolyzers with power plants for hydrogen production e.g. Refs. [11–13]. In these systems, the high temperature SOE was analyzed as part of larger power systems such as solar or nuclear power plants. Subsequently, more emphasis has been dedicated to investigating SOE among these focused studies. A parametric study was conducted by Ni et al. [14] to evaluate the electrolysis cell polarizations at different operating conditions through a one-dimensional model. Ni et al. [15] also, conducted an energy and exergy analysis of an SOE for hydrogen production. They pointed out that SOE is expected to switch from an endothermic mode to an exothermic mode as a result of the reduction in the operating temperature. This is due to the increase in the cell polarizations (irreversibilities) which is dissipated in the form of heat that may exceed the required thermal energy. It was also shown that the difference between energy and exergy efficiencies decreases with the reduction in the heat input to total energy required. Ni et al. [16] investigated concentration overpotentials of solid oxide cell operating in electrolysis cell mode in comparison with fuel cell mode. They reported that in electrolysis mode the hydrogen electrode shows more vulnerability to high concentration polarization, in contrast to fuel cell mode, where oxygen electrode was more vulnerable. In addition, the same authors reviewed the development of hydrogen production using SOEC [17]. Henke et al. [18] investigated high pressure operation of SOE. Likewise Todd et al. [19] studied high temperature and high pressure SOE operation. Manage et al. [20] discussed the technical and economic aspects of hydrogen production from different technologies. They focused on the economic feasibility of the high temperature SOEs. They showed that SOE technology can achieved an efficiency of up to 90%. However, for SOEs to be economically competitive with conventional technologies such as SMR, which currently produces hydrogen at $ 2.50/kg, environmental measures and regulation must be introduced to leverage carbon-free hydrogen and electricity resources. Buttler et al. [21] conducted a techno-economic study on high temperature SOE-based hydrogen production using a 1-D model. They concluded that high temperature integration might be more economically viable compared with the thermoneutral operation.

Numerous researchers have performed a diverse range of experimental investigations at a laboratory scale with SOECs and stacks. For example, Idaho National Lab has been pursuing high temperature SOE-based hydrogen production through nuclear plant integration [22,23]. They also developed a three-dimensional computational fluid dynamic (CFD) model to evaluate the distribution of important performance parameters across a 60 planar cell stack. Their parameters included temperature, current density, Nernst potential, polarizations, and hydrogen production [24]. Brisse et al. [25] conducted a test of a button SOEC and reported the cell performance at different humidity levels. They also reported some electrochemical spectroscopy characterization of the cell. Petipas et al. [26] measured the SOEC performance under cyclic operation to examine cell degradation at the transient condition. Ebbesen et al. [27] reported an SOEC test under different operating temperatures and reactant compositions. Furthermore, this study, in addition to others e.g. Refs. [28,29], investigated co-electrolysis of water and carbon dioxide to produce syngas which can be used fuel cells to reproduce power in a carbon-neutral fashion.

The open literature includes numerous modeling studies where most of them are dedicated to investigate the performance of a high temperature electrolysis process either at cell scale level or at large-scale electrolyzer integrated into power plant systems. Therefore, the current study targets the analysis of a high-temperature-based electrolysis unit which can