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A performance assessment study on solid oxide fuel cells for reduced operating temperatures

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ABSTRACT

In this paper, a conventional solid oxide fuel cell (SOFC) is modeled, and its performance is assessed to investigate the main challenges that limit low temperature operation. SOFCs have numerous advantages over other fuel cell technologies; however, a major drawback of SOFCs is the high operating temperature (over 600 °C) which significantly reduces SOFCs lifetime and constrains manufacturing materials to costly produced composites. Therefore, the development of a low temperature solid oxide fuel cell (LT-SOFC) will improve the cost effectiveness of this technology and thereby enhance efficient energy utilization and contribute to CO_2 emission reduction. In this regard, a model is employed to predict the conventional SOFC performance under different operating and design conditions, in general, and at low operating temperatures, in particular. Furthermore, the contribution of each of the polarizations is evaluated. The model results are validated through a comparison with published experimental data and found to be in a good agreement with a maximum possible error value of 10.3% in cell potential and power density output. The results show that conventional SOFCs are vulnerable to a significant performance reduction when operating at low temperatures (below 600 °C). In addition, the polarization that SOFCs experience at low operating temperatures is mainly attributed to electrolyte ohmic loss.

Introduction

A fuel cell is defined as an electrochemical device that directly converts fuel chemical energy to electrical energy [1]. Fuel cells mainly consist of an electrolyte positioned between two electrodes: cathode and anode. The global growing interest in fuel cells is derived by the numerous promising characteristics of this technology such as: high energy efficiency at full and partial load operation, low hazardous emissions, flexible system sizing, and quiet operation. In addition, fuel cells are being viewed as a promising candidate to replace internal

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combustion engines which are a major CO_2 emission producer [2]. Other various applications range from powering mobile phones and small electronic devices to residential and distributed cogeneration systems. Fuel cells can be classified according to the type of electrolyte used, the type of ion transferred, the type of reactants used and the operating temperature range [3].

SOFCs consist of all solid components, including an oxide ion conductor electrolyte which eliminates the electrolyte management challenges existing in other types of fuel cells. This feature also allows for an easier cell and stack fabrication; therefore SOFCs are produced in different geometry designs such as planar, tubular, and monolithic. In addition, SOFCs offer fuel flexibility as they are capable of directly utilizing both hydrogen and carbon monoxide as fuels to produce electricity. The operating temperatures of SOFCs are in the range of (700–1000 °C) which increases the kinetics of electrochemical reactions, enables the internal reforming processes of some hydrocarbon fuels such as methane, and increases SOFCs tolerance to impurities associated with reactants [1]. On the other hand, the high operating temperature also creates some challenges that oppose the widespread commercialization of this technology. For example, the high operating temperature significantly reduces cell lifetime and restricts material options that can be used for sealing and interconnect to high cost composites. Therefore, it is very desirable to reduce the operating temperature of the SOFC which will subsequently improve stack durability and reduce production cost [4]. In addition, reducing the operating temperature will not affect any advantages of SOFC such as: reforming integration, impurities tolerance and high quality exhaust energy.

However, for a conventional SOFC that uses yttria (Y_2O_3) stabilized zirconia (ZrO_2) or (YSZ) as an electrolyte material, reducing the operating temperature will significantly reduce the ionic conductivity and will result in considerable loss in cell potential [5]. The solution to this problem was the focus of numerous studies which were dedicated to the development of alternative electrolyte materials to replace (YSZ) and be able to better demonstrate ion conductivity at an operating temperature in the range of (500–700 °C) [6–10]. For instance, in order to reduce SOFC operating temperature, Ceres Power Ltd. used gadolinia-doped ceria (CGO) as an electrolyte material for an LT-SOFC that can operate below 600 °C. Further, a model was developed to assess cell polarization including the effect of electronic conductivity at full and part load operation [11]. Pramuanjaroenkij et al. [12] modeled SOFCs, with YSZ and CGO as an electrolyte material, to predict cell performance. A comparison between using YSZ and CGO electrolytes showed that SOFC with YSZ electrolyte produces higher power density compared with the SOFC with CGO only at an operating temperature of 750 °C and higher. However, the main drawback in the use of CGO as an electrolyte instead of YSZ in SOFC is that CGO tends to have mixed conductivity, particularly in a reducing environment such as that in the anode side. It can be clearly noticed that the advancement in developing an alternative electrolyte material for LT-SOFC predominantly depends on experimental research which can be costly and time consuming. Additionally, all proposed alternative electrolyte materials, so far, are still in the early stages and not yet as mature as YSZ.

Another approach to reduce the operating temperature of SOFC is to investigate different design geometries of conventional SOFCs such as reducing electrolyte thickness to achieve acceptable cell performance at relatively low temperatures compared to a nominal SOFC operating around 1000 °C. A number of researchers have developed different types of numerical and analytical models to predict YSZ-based SOFC performance; e. g. Refs. [13–18]. These models vary in complexity and desired outcomes. Moreover, the fairly developed knowledge of the physical and chemical properties of YSZ-based SOFC components facilitate reliable results. Further details can be found in Kakac et al. [19] where a literature review was conducted on numerical modeling of SOFCs, including the various mathematical models for tubular, planar and monolithic cell geometries. Colpan et al. [20] performed a thermodynamic model for a direct internal reforming planar SOFC, operating on syngas. Their results showed that selecting the fuel utilization factor has a significant impact on power output and cell efficiency. Costamagna et al. [21] developed a micro-model of SOFC electrodes and obtained a significant relation between the electrodes' structure design and resistance. Ni [22] developed a two-dimensional model to evaluate CO_2 and CH_4 fed SOFC performance. It was noticed that the power output of SOFCs decreased with reducing the operating temperature due to the reduction in cell voltage. Hussain et al. [23] modeled planar SOFCs and pointed out that ohmic polarization was a major loss contributor at an operating temperature of 800 °C. Xia et al. [24] developed a three-dimensional model to investigate the effects of operations and structural parameters on the performance of a planar one-cell SOFC stack. Ni et al. [25] modeled a methane fed SOFC, and showed that the performance of an oxygen conducting electrolyte SOFC is higher than that with a proton conducting electrolyte due to the later ohmic polarization.

There has been a significant interest in understanding the performance of SOFCs at low operating temperature as clearly observed through presented literature. This interest is essentially promoted by the promising potential of LT-SOFC in terms of better durability, cost competitiveness, and application diversity. However, limited studies have considered optimizing conventional SOFC design for maximizing the cell power output at reduced operating temperature. Therefore, the present study investigates the performance of planar SOFC at low operating temperature. The effects of other operating and design conditions on the cell performance are also examined. Moreover, the following specific objectives are expected to make some contributions to the area of research:

- Utilizing a simple, but expressive model that can further be integrated with an optimization algorithm to optimize cell operation and design parameters without changing electrolyte and electrode materials.
- Evaluating the electrolyte ohmic polarizations for different thicknesses at low operating temperatures.
- Addressing the tradeoff between the increase in the ohmic polarization, with increasing electrode thickness, and