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Mathematical modelling and experimental validation of an anode-supported tubular solid oxide fuel cell for heat and power generation

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A tubular solid oxide fuel cell is designed to evaluate its current/voltage characteristics for validating an isothermal model. The model is divided into six subsystems. It can simulate performance based on mass/momentum transfer, diffusion through porous media, electrochemical reactions, polarization losses and heat generation inside the subsystems. The significance of this investigation involves the conversion of a macro-tubular solid oxide fuel cell into six connected micro-reactors in series. The model can successfully predict the dependence of current density on cell potential (observed experimentally). Thermal energy generation by means of fuel reactions as well as voltage irreversibility losses are simulated to account for efficiency losses using the experimental data. Increases in the efficiencies of electrical and thermal power generation by 50.11% and 47.54% are observed when the operating temperature rises from 923 to 1023 K. In addition, the effect of flow pressures and flow rates on solid oxide fuel cell performance is simulated and validated with the experimental results.

1. Introduction

Significant progress has been achieved on sustainable energy and environmental protection in the last few years; however, more research and developments are needed to solve the energy issue and to reduce harmful emissions, to improve the standard of living in our world [1]. Amongst different types of small-scale power generation systems fuel cells have attracted considerable attention in the past two decades because of the worldwide need for more efficient and greener power generation systems. SOFCs (solid oxide fuel cells) are considered most promising for power generation due to their high efficiencies [2] and fuel flexibility [3]. Additionally, SOFCs produce high temperature steam that may be harnessed for applications such as combined cycle power generation or domestic water heating. This hybrid operation results in an overall system efficiency in excess of 80% [4].

The development of SOFC generation systems, however, is still facing some challenges, such as achieving lower costs at improved lifetimes. To achieve such goals, a better understanding of the underlying processes and reactions is necessary. There are many experimental studies on SOFCs to investigate new materials, develop single SOFC designs and advancement of cell manufacturing methods. Two significant experimental studies have been performed by Singhal [5] and Kendall [6]. Singhal [5] studied the materials and fabrication methods for different cell components as well as their effects on cell performance at three different operating temperatures. The SOFC was fuelled with hydrogen. The fuel cell consisted of two tubes (Westinghouse design). The inner was the injection tube and the outer was a cell tube that was closed at the end. It was observed that higher operating temperatures improved the fuel cell performance. It was also shown that operations at elevated pressures resulted in higher powers at any

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current density due to an enhanced Nernst potential and reduced cathodic polarization [5]. However, it is not clearly shown, which amongst fuel and air flow pressures, has a more significant effect on the system performance. The effect of gas flow rates has also not been investigated.

Kendall et al. [6] investigated a micro-tubular SOFC fuelled with methane. The purpose of their work was to conduct experiments in which methane was fed directly into the micro SOFC operating under different conditions. The reactions were analysed electrochemically by observing the Nernst potential and the change in voltage with temperature. Also, the carbon deposited on the anode of the cell was investigated by temperature programmed oxidation, using a mass spectrometer to detect oxidation products from the carbon layers. In continuation of Kendall's study, Calise and co-workers [7] investigated the thermodynamic and electrochemical performance of an anode-supported micro-tubular SOFC fuelled with different combinations of H_2, CO, CH_4 and H_2O at 823 K, to determine the cell polarization curves under several load cycles. The researchers reported that the cell fuelled with light hydrocarbons was sensitive to carbon deposition, which significantly reduced performance. Performance degradation was also detected when hydrogen was employed.

However, in a different work, Li et al. [8] studied a Ni/AL_2O_3 cermet supported tubular SOFC using a biomass based syngas as fuel. They investigated the electrical performance and compared their results with those for an H_2 fed system. The results illustrated that the maximum power density for the H_2-based system was 0.44 W/cm^2 at 900 °C while that for the system operating on syngas was 0.32 W/cm^2.

Zhao and Virkar [9] performed an experimental investigation on an SOFC operating with hydrogen as the fuel. The effect of various parameters on cell performance and polarization was studied at temperatures ranging from 872 to 1072 K. The parameters evaluated included electrolyte thickness, cathodic interlayer thickness, anodic support thickness and anodic support porosity.

However, such experimental works failed to optimize the effect of cell temperature, pressure and flow rates on cell performance. Thus a significant gap has remained in the literature that needs addressing. Moreover, it is extremely difficult for pure experimental methods to de-convolute internal transport phenomena due to the complexity of internal multi physical processes. Furthermore, experimental investigations on SOFCs are time-consuming and expensive.

Mathematical modelling is an economical means for investigating the fuel cell to optimize and control its behaviour, increase its efficiency and performance, as well as to improve its lifetime. Modelling and simulation can provide detailed information about the phenomena and electrochemical performances that may not be ascertained from experimental investigations [10]. Amongst many mathematical modelling and simulation studies, there are some works, concerned with different aspects of SOFCs, which introduce a holistic view of the system's characterisation such that current researchers may adopt and improve them [11–14]. However, since the simulation results are only an estimate of the real system, an important step forward involves experimental validation which is neglected by several authors including Xenos et al. [15] and He et al. [16]. At present there is limited work on the experimental validation of SOFC models as is evident from current literature reports [17–20]. Therefore, modelling, simulation and experimental studies in parallel is essential for validation and improvement of the fuel cell performance and efficiency.

Suwanwarangkul et al. [21] developed a 2-D isothermal model of an SOFC operating with syngas. They presented a comparison between modelling and experimental data for the cell operating at various flow rates and temperatures of 1073.15 and 1173.15 K. They observed that cell performance was independent of fuel flow rate, while the measured values showed a minor enhancement in cell performance at higher flow rates. This effect was more obvious at the lower temperature.

The aim of this work is to develop a detailed model for a single tubular SOFC fed with hydrogen and to validate it experimentally (by studying its voltage/current characteristics) at temperatures of 923 and 1023 K. At these operating temperatures, material degradation is not expected to be of much importance [6]. A significant gap has remained in the literature in terms of studying the effect of temperature, pressure and flow rates on cell performance. Thus, the effect of these parameters on cell performance are also studied and validated in this investigation. The significance and novelty of this research lies in the conversion of a macro-tubular SOFC into six connected micro-reactors in series. This may be a rather new modelling approach in the field of tubular SOFC research, within the knowledge of the authors, and the results obtained herein may support the future commercialization of the technology.

2. Experimental

The experimental setup consists of four main parts: a single tubular SOFC, a fuel cell testing system, a split vertical furnace, and a data acquisition device. The in-house designed SOFC is made up of a single ceramic tube. The electrochemical cell is an anode supported reactor. The cell consists of an 8 YSZ electrolyte (8 mol. % YSZ) that is approximately 3×10^{-5} m thick (fabricated by means of tape casting). The electrolyte allows oxide ions to pass through it and reach the anodic surface, where they combine with hydrogen to form water. Inside the cell tube is a 2×10^{-4} m thick Ni–Cu-YSZ anode while the outside consists of a 3×10^{-5} m thick LSM ($La_{0.7}Sr_{0.2}MnO_{3-\Delta}$) cathode. The structures of both electrodes are porous enough to permit rapid mass transfer of reactant and product gases. The cathodic material has low levels of chemical reactivity with the electrolyte, which extends the lifetime of the material. However, it is a poor ionic conductor. The electrochemical reaction occurs when both fuel and air flow into the SOFC simultaneously. A photo of the fuel cell is shown in Fig. 1.

The SOFC and its test bed system were purchased from WonA-Tech (South Korea). All gases were supplied by Linde (Malaysia).

The anodic part of the cell was placed on a current collector made of silver mesh (Goodfellow, UK). This assembly was spot welded on to two silver wires (Goodfellow) to act as current and voltage probes. The cathodic part was directly exposed to ambient air that flowed in to the cell via natural convection. The cell test rig was confined in a temperature-controlled furnace to ensure that it could be operated isothermally. Three thermocouples were located in the vicinity of both electrodes to measure the temperatures.

The goal of the setup was to analyse the effect of different operating parameters on the fuel cell. Tables 1 and 2 present the parameters and operating conditions employed.

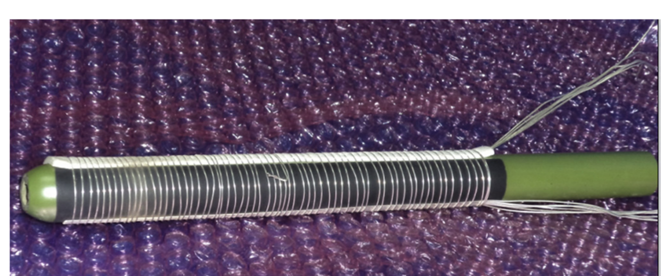

Fig. 1. Photo of the anode supported tubular SOFC used in this investigation.