Journal of Power Sources 384 (2018) 367–378

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Numerical analysis on effect of aspect ratio of planar solid oxide fuel cell fueled with decomposed ammonia

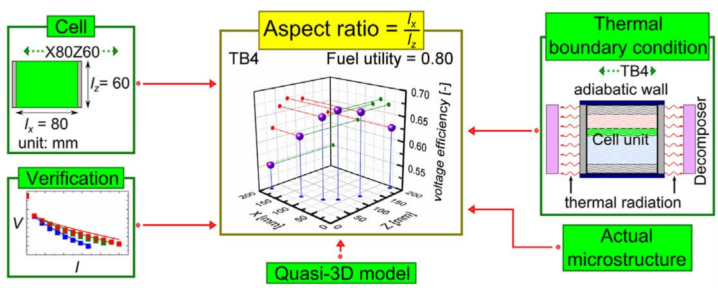
Wee Choon Tan[a,b,*], Hiroshi Iwai[a], Masashi Kishimoto[a], Grzegorz Brus[c], Janusz S. Szmyd[c], Hideo Yoshida[a]

[a] Department of Aeronautics and Astronautics, Kyoto University, Nishikyo-ku, Kyoto, 615-8540, Japan
[b] School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Perlis, Malaysia
[c] Department of Fundamental Research in Energy Engineering, AGH University of Science and Technology, 30-059 Krakow, Poland

HIGHLIGHTS

- Effect of cell aspect ratio with indirect ammonia decomposition is investigated.
- The developed model is verified with experimental data without parameter tuning.
- Modification of aspect ratio can improve the voltage efficiency as much as 22.6%.
- Suitable aspect ratio ensures sustainability of ammonia decomposer next to SOFC.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
SOFC
Simulation
Aspect ratio
Decomposed ammonia
Fuel utility factor
Voltage efficiency

ABSTRACT

Planar solid oxide fuel cells (SOFCs) with decomposed ammonia are numerically studied to investigate the effect of the cell aspect ratio. The ammonia decomposer is assumed to be located next to the SOFCs, and the heat required for the endothermic decomposition reaction is supplied by the thermal radiation from the SOFCs. Cells with aspect ratios (ratios of the streamwise length to the spanwise width) between 0.130 and 7.68 are provided with the reactants at a constant mass flow rate. A parametric study is conducted by varying the cell temperature and fuel utility factor to investigate their effects on the cell performance in terms of the voltage efficiency. The effect of the heat supply to the ammonia decomposer is also studied. The developed model shows good agreement, in terms of the current-voltage curve, with the experimental data obtained from a short stack without parameter tuning. The simulation study reveals that the cell with the highest aspect ratio achieves the highest performance under furnace operation. On the other hand, the 0.750 aspect ratio cell with the highest voltage efficiency of 0.67 is capable of thermally sustaining the ammonia decomposers at a fuel utility of 0.80 using the thermal radiation from both sidewalls.

1. Introduction

Recently, ammonia has been identified as a potential fuel for solid oxide fuel cell (SOFC) systems owing to its high gravimetric and volumetric energy density, ease of storage and transportation, and carbon-free nature. Additionally, the leakage of ammonia can be easily sensed even at concentrations of under 1 ppm [1]. Ammonia must undergo a decomposition reaction to convert it into hydrogen as the main fuel for SOFCs. The decomposition of ammonia is an endothermic process, which helps to reduce the local anode temperature under a direct

* Corresponding author. Department of Aeronautics and Astronautics, Kyoto University, Nishikyo-ku, Kyoto, 615-8540, Japan.
E-mail address: tweechoon@unimap.edu.my (W.C. Tan).

https://doi.org/10.1016/j.jpowsour.2018.03.011
Received 7 December 2017; Received in revised form 6 February 2018; Accepted 4 March 2018

ammonia supply. It also increases the overall system efficiency through the reduction of energy consumed to supply the excess air in the air channel [2]. However, Meng et al. [3] reported that a high flow rate or low temperature of ammonia can result in poor cell performance in the case of direct ammonia decomposition. A higher flow rate of ammonia supplied to SOFCs leads to greater overall endothermic heating, while a lower temperature of the supplied ammonia leads to a lower operating temperature. Both factors increase the voltage losses and decrease the cell performance. Ammonia can also be supplied through an external decomposer. In such a case, the decomposer requires a heat source to sustain the endothermic reaction. This heat can be supplied from the stack, afterburner, heat exchanger or their combination.

An electrochemical reaction occurs in the active area in a single cell. Increasing the active area is a simple but effective approach to achieve a higher current output. Although the maximum active area tends to be limited by the available manufacturing technologies, there are still design options with different cell aspect ratios within the same active area. The aspect ratio is defined as the ratio of the streamwise length to the spanwise width. Most studies have been conducted with an aspect ratio of exactly unity for both laboratory cells [4–8] and commercial cells [9,10]. Although there have also been a few studies conducted with cells having other aspect ratios [11–13], none of them proposed guidelines for designing SOFCs in terms of the aspect ratio in view of the heat balance, thermal leakage, and operating conditions. All of these factors are considered important, especially for SOFCs that are fed by indirectly decomposed ammonia.

In principle, the effect of aspect ratio can be investigated by three-dimensional (3D) numerical models; however, it is not realistic due to its extremely high computational cost. Therefore, there are extensive works where the 3D models were simplified into quasi-2D or quasi-3D model by employing one-dimensional analytical [14,15] and numerical [16,17] approaches for the mass transport in the electrodes. Iwai et al. [18] proposed a quasi-3D numerical model to analyze an intermediate temperature SOFCs with direct internal methane reforming. The temperature gradient along the cell thickness direction was neglected. Similarly, Lai et al. [19] developed a quasi-2D numerical model, which can analyze a planar SOFC stack consisting of 96 cells. However, this model is limited to co- and counter-flow configurations as it ignores the distribution perpendicular to the flow direction. Park and Min [20] proposed a quasi-3D non-isothermal dynamic model to analyze a proton exchange membrane fuel cell. All the above mentioned models can significantly reduce the computational cost and are capable of performing stack level analysis.

The aim of the present work is to study the effect of the aspect ratio of an SOFC fueled with indirectly decomposed ammonia on its performance by using a quasi-3D numerical model. The numerical analysis considered cells with aspect ratios from 0.130 to 7.68 with a constant active area of 4800 mm^2 under constant mass flow rates of the reactants. Actual microstructure information of electrodes obtained from 3D microstructural analysis was taken into account in the numerical simulation. A short-stack experiment was conducted to verify the developed model, where the supplied fuel was hydrogen diluted with nitrogen. A parametric study is performed using the verified model under the same fuel utility operation to study the performance of cells with various aspect ratios in terms of their voltage efficiency. The effects of the operation temperature, fuel utility, and thermal radiation from the SOFC to sustain the ammonia decomposer located next to the SOFC are also discussed.

2. Experiment

The power generation experiment was conducted using an SOFC modular stack test bench that was designed and produced by SOLIDpower S.p.A. A short stack consisting of six cells with a standard power output of 100 W from SOLIDpower S.p.A. was tested. The SOFC analyzed in this study was an anode-supported cell consisting of a nickel/yttria-stabilized zirconia (Ni/YSZ) cermet anode, a dense YSZ electrolyte, a gadolinium-doped ceria (GDC) barrier layer, a lanthanum strontium cobalt ferrite (LSCF-GDC) cathode functional layer, and a LSCF cathode current collector. The cell had an active size of 80 mm × 60 mm with thicknesses of 240, 8, 4, and 50 μm for the anode, electrolyte, GDC barrier layer, and cathode layer, respectively. The supplied fuel was hydrogen diluted with nitrogen. Ammonia could not be supplied owing to for a limitation on the system regarding the inlet gas composition. In the present configuration, the gas composition cannot exceed 70% of the hydrogen content in the fuel to prevent an excessive increase in temperature in the afterburner. Nevertheless, the supplied fuel enabled the model to be verified because the same supplied fuel was considered in the numerical analysis during model verification. The electric furnace was operated at a temperature of 973, 1023, or 1073 K. Hydrogen and nitrogen were supplied to the six-cell stack at flow rates of 1.8 and 1.2 L min^{-1}, respectively. At the same time, air was supplied at a flow rate of 18.0 L min^{-1}. Details of the short-stack experiment can be found elsewhere [21,22].

The 100 W short stack underwent an aging experiment, as reported in Ref. [23], and it was not possible to obtain the cell microstructure from the short stack during the aging experiment. The anode microstructure of the cell was obtained from a new supplementary cell, also from SOLIDpower S.p.A., together with that of the short stack. This supplementary cell was reduced and considered to be identical to the cells in the short stack. It was also assumed that the cells in the short stack did not undergo any microstructure changes after the initial power generation experiment. The supplementary cell was then impregnated using epoxy resin under vacuum conditions before being cut and polished for focused ion beam scanning electron microscope (FIB-SEM) tomography. The 3D microstructure was reconstructed using AVIZO software based on a series of 2D microstructure images obtained from FIB-SEM tomography. Details of the anode microstructure quantification procedure can be found elsewhere [21]. The cathode microstructure of the cell was obtained from the 300 W stack [24], which was also from SOLIDpower S.p.A. The cathode consisted of a GDC barrier layer, a LSCF-GDC functional layer, and a LSCF current collector layer. The thin GDC barrier layer prevents any reaction between the LSCF and the YSZ electrolyte while allowing the transportation of ions. On the other hand, the LSCF current collector layer is responsible for the transportation of gas species and electrons. The volume fraction and tortuosity factor of the pore phase in the LSCF-GDC functional layer were similar to those in the LSCF current collector layer. In addition, because the electron conductivity is generally a few orders higher than the ionic conductivity, the electronic conductivity resistance is normally ignored in the numerical analysis by researchers. Hereafter, the cathode is referred to the LSCF-GDC functional layer. The microstructure information is summarized in Table 1.

3. Numerical modeling and major assumptions

A cell unit consisting of top and bottom separators, fuel and air channels, and a cell or also known as a positive-electrolyte-negative assembly (PEN), was modeled as shown in Fig. 1(a). A unique-feature of the considered cell unit is the design of the fuel and air channels, which

Table 1
Microstructure information.

Parameters	Anode [21]	Cathode [24]
Average radius of pore phase [μm]	0.566	1.01
Volume fraction of pore phase [-]	0.251	0.410
Volume fraction of ionic phase [-]	0.383	0.260
Tortuosity factor of pore phase [-]	20.1	2.24
Tortuosity factor of ionic phase [-]	2.44	20.3
Volumetric density of TPB line [m/m^3]	4.97×10^{12}	–
Volumetric density of DPB area [m^2/m^3]	–	6.67×10^{6}