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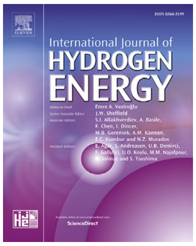

Analysis of a solid oxide fuel cell and a molten carbonate fuel cell integrated system with different configurations

Prathak Jienkulsawad [a], *Dang Saebea* [b], *Yaneeporn Patcharavorachot* [c], *Soorathep Kheawhom* [a], *Amornchai Arpornwichanop* [a,*]

[a] *Computational Process Engineering Research Unit, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand*
[b] *Department of Chemical Engineering, Faculty of Engineering, Burapha University, Chonburi 20131, Thailand*
[c] *School of Chemical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand*

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ABSTRACT

A solid oxide fuel cell with internal reforming operation is run at partial fuel utilization; thus, the remaining fuel can be further used for producing additional power. In addition, the exhaust gas of a solid oxide fuel cell still contains carbon dioxide, which is the primary greenhouse gas, and identifying a way to utilize this carbon dioxide is important. Integrating the solid oxide fuel cell with the molten carbonate fuel cell is a potential solution for carbon dioxide utilization. In this study, the performance of the integrated fuel cell system is analyzed. The solid oxide fuel cell is the main power generator, and the molten carbonate fuel cell is regarded as a carbon dioxide concentrator that produces electricity as a by-product. Modeling of the solid oxide fuel cell and the molten carbonate fuel cell is based on one-dimensional mass balance, considering all cell voltage losses. Primary operating conditions of the integrated fuel cell system that affect the system efficiencies in terms of power generation and carbon dioxide utilization are studied, and the optimal operating parameters are identified based on these criteria. Various configurations of the integrated fuel cell system are proposed and compared to determine the suitable design of the integrated fuel cell system.

Introduction

A reduction of carbon dioxide (CO_2) emission has presently been an important concern for conventional thermal power plants. Although renewable and sustainable energy sources can be used in power generation to reduce CO_2 emission, most power plants are still based on fossil fuels and technology that can capture, store and utilize CO_2 should be applied to mitigate CO_2 emission [1–4].

High-temperature fuel cells (HTFCs) are high-performance power generation devices that can replace a conventional combustion-based power generator [5] because heat produced from the fuel cell can be used in fuel processing and heat generation systems [6]. Moreover, HTFCs can directly use various types of fuels via direct internal reforming operation

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* *Corresponding author.*
E-mail address: Amornchai.A@chula.ac.th (A. Arpornwichanop).

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[7–9]. Syngas with tar can be also used in SOFCs at some tolerances [10]. As methane can be easily obtained during many production processes, such as petrochemical, refining and fermentation processes, it is widely used as a fuel for HTFCs [11–13].

Solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) are among the HTFCs that have higher electrical efficiency and lower CO_2 emission than the combustion-based power plants [14]. For power plant applications, the SOFC is more dominant due to a relatively higher power density and is less corrosive than the MCFC, which uses molten salt electrolyte that can be lost during a long term operation [15]. When considering the direct internal reforming operation of SOFC, excess steam input is needed to avoid carbon formation on the fuel cell anode [16]. However, excessive steam will dilute the hydrogen concentration and cause hydrogen deficiency in the cell stack. This factor increases the formation of NiO on the anode and degrades the cell performance. This incident also occurs when the SOFC is run at a higher fuel utilization rate and thus, the SOFC is operated at a moderate fuel utilization rate [17,18]. Under this operating condition, the anode exhaust gas is still valuable because of remaining fuels, such as hydrogen and carbon monoxide. These useful fuels can be directly used for producing additional power [19]. Frangini and Masi [20] reviewed the use of MCFC in advanced and sustainable energy sectors with three application categories; generation/conversion/storage of energy, materials and manufacturing processes, and applications to advanced gas processing and gasification technologies. In the advanced gas processing application, the MCFC has recently gained attention as an alternative CO_2 utilization technology [1,21,22]. Wee [1] claimed that MCFCs act as CO_2 concentrators or separators when integrated into traditional power plants, and they can increase the overall electrical efficiency and reduce CO_2 emission per power generation because of additional power generation and an increase in CO_2 recirculation inside the system. Currently, MCFCs are used in the bottom stream in a power plant to utilize CO_2 and reduce CO_2 emission [23]. In fact, a standalone MCFC could not actually reduce an amount of CO_2 emission, however, CO_2 can be utilized by a MCFC. Although the SOFC itself can produce electricity without generating CO_2, the fuel processing to produce hydrogen for SOFCs involves the production of CO_2 as a byproduct. The integration of SOFCs with MCFCs could relieve this concern, as MCFCs utilizes CO_2 as a reactant in electricity generation. Thus, the SOFC and MCFC integrated system is not only a potential solution for increasing fuel utilization and power but also utilizes carbon dioxide. McPhail et al. [6] indicated the possibility of merging SOFC and MCFC electrolytes by creating a composite electrolyte based on carbonate-impregnated ceramics, as both the fuel cells have a similarity in their operating temperature and anode catalyst. Jienkulsawad et al. [24] studied the integrated system of the SOFC, as a main power generation and the MCFC, as a carbon dioxide concentrator. They proposed that the exhaust gases of the SOFC should be directly introduced to the MCFC and a recirculation of the exhaust gas from an after-burner to MCFC can enhance the energy efficiency and decrease the CO_2 emission. However, NiO formation affecting the SOFC performance is not considered.

As the configuration of the SOFC-MCFC integrated system is important and affects the system performance, in this study, the performance of such an integrated fuel cell system with different configurations with and without feed separation and exhaust gas recirculation is investigated. Air fed to SOFC in parallel configurations is considered. The energy efficiency and CO_2 emission coefficient (CEC) are key parameters for comparing the fuel cell system performance. Moreover, heat duty requirement and the effect of the NiO formation caused by hydrogen deficiency on the fuel cell performance are also taken into account.

System configuration

A planar SOFC consists of Ni-YSZ as the anode, YSZ as the electrolyte and YSZ-LSM as the cathode. For MCFCs, a Ni-alloy is used as the anode, Li_2CO_3/Na_2CO_3 is used as the electrolyte and NiO is used as the cathode. In the fuel cell integrated system, the steam-to-carbon ratio is fixed at 2 and 10% pre-reforming in order to avoid carbon formation [14,16]. SOFC acts as the main power generator without NiO formation. Produced CO_2 is fed to the MCFC as a carbon dioxide utilizer along with producing electricity as a by-product.

In this study, different configurations of the integrated system, as shown in Fig. 1, are analyzed and compared to determine the suitable system design in terms of power generation and carbon dioxide utilization. For comparison, units are set at the same operating condition in each design to evaluate the effect of different designs and whether NiO formation is possible or not in each system design. The operating conditions of each unit is shown in Table 1 and the fuel cell dimension is given in Table 2. For the first configuration (A) (Fig. 1(a)), the MCFC is placed at the bottom of the existing SOFC system. The reformed gas is divided to operate the MCFC and the exit-gas from the existing SOFC system is the carbon dioxide source of the MCFC system. The anode off-gas of the MCFC is fully recirculated to burn the faction of remaining fuel. The configurations that are used to compare with configuration (A) are designed by fuel flow pattern between two fuel cell types because the fuel is the main key of power generation by fuel cell. Configuration (B) (Fig. 1(b)) represents a series configuration and a parallel configuration is shown in (C) (Fig. 1(c)). An additional configuration (D) is represented as series-parallel combination configuration. In configuration (B), both the anode and the cathode off-gas from the SOFC are directly fed to the MCFC and portion of the exhaust gas from an after-burner is recirculated to the MCFC. In this configuration, the MCFC uses the remaining fuel from the SOFC, which means this design can improve the fuel utilization of the integrated system, and examines its performance under a lower fuel concentration fed to the MCFC. In the third design (C), the reformed gas is separately fed to the SOFC and the MCFC. Air is separated according to the amount of reformed gas fed to the SOFC. The cathode off-gas is mixed with air and fed to the MCFC. The anode off-gas from the SOFC and the MCFC are mixed with the remaining gas from the cathode of the MCFC and burnt in the burner and portion of the exhausted gas is recirculated. The differences between this configuration and configuration (A) are the recycled steam,

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