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Effect of anode–cathode exhaust gas recirculation on energy recuperation in a solid oxide fuel cell-gas turbine hybrid power system

Dang Saebea [a], Suthida Authayanun [b], Yaneeporn Patcharavorachot [c], Amornchai Arpornwichanop [d,*]

[a] Department of Chemical Engineering, Faculty of Engineering, Burapha University, Chonburi 20131, Thailand
[b] Department of Chemical Engineering, Faculty of Engineering, Srinakharinwirot University, Nakorn Nayok 26120, Thailand
[c] School of Chemical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand
[d] Computational Process Engineering Research Unit, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand

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ABSTRACT

A solid oxide fuel cell-gas turbine (SOFC-GT) hybrid system supplying liquid fuel as ethanol exhibits promise as an auxiliary power unit. In this study, the recirculation of anode and cathode exhaust gas in the SOFC-GT system is proposed to improve the efficiency of heat management in the SOFC-GT hybrid system. The key operating parameters, such as fuel utilization factor and the cell and GT temperatures, are analyzed in terms of the performance of the SOFC-GT hybrid systems. The simulation results show that the recirculation of anode and cathode exhaust gas has a direct impact on the turbine performance. To maintain the inlet temperature of the small turbine in the range of 873–1223 K, the amount of fuel and air added to the combustor to control the turbine inlet temperature on the system performance is also investigated. A SOFC-GT hybrid system with both anode and cathode exhaust gas recirculation achieves the highest system and thermal efficiency.

1. Introduction

The world population increase drives the increase in energy demand. Moreover, pollutant emissions from conventional power plants are a serious environmental problem. To address the above problems, researchers are seeking to develop more efficient power generation. The solid oxide fuel cell-gas turbine (SOFC-GT) hybrid system is an alternative power generation solution for distributed power generation market due to its clean electrical energy production and high efficiency. In an SOFC-GT hybrid system, the waste heat from SOFC can be used directly in the gas turbine as the bottom cycle. The efficiency of this hybrid system can reach up to 70% [1].

Most SOFC systems run on natural gas; however, the deficiency of fossil fuels as a limited and non-renewable resource has been increasing even though it is a cost-effective feedstock. Ethanol is currently considered a promising fuel for SOFCs because it is a renewable fuel produced from agricultural products. It has relatively high hydrogen content and is easy to store, handle, and transport safely [2,3]. Hence, ethanol is a suitable fuel for remote areas where a natural gas pipeline network is unavailable, as well as a promising alternative fuel for medium-scale power generation in SOFC-GT hybrid systems.

The variation in fuel type supplied for the SOFC-GT hybrid system has a great impact on the optimal operational parameters for the system and the system outputs [4,5]. Thus, the design and operational condition of the SOFC-GT hybrid system should be suitable for the fuel type in the system. In the utilization of ethanol as fuel for the SOFC system, a direct ethanol supply to the SOFC leads to the degradation of anode catalysts due to carbon formation [6]. To avoid this problem, an external reformer is integrated with the SOFC system for hydrogen production. However, the external reformer for ethanol steam reforming requires the high heat input because of its strong endothermic reaction. Additionally, the external reforming SOFC system requires a higher air supply for SOFC than the direct internal reforming SOFC system [7]. The increased air flow to the system has an adverse impact on the system efficiency because high heat input is needed to preheat air before introduction to the SOFC. The aforementioned problems

* Corresponding author. Tel.: +66 2 218 6878; fax: +66 2 218 6877.
E-mail address: Amornchai.A@chula.ac.th (A. Arpornwichanop).

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require efficient energy management in the SOFC-GT hybrid system.

Generally, the majority of SOFC-GT hybrid system configurations can be divided into atmospheric and pressurized SOFC-GT hybrid systems. Comparatively, the pressurized hybrid system has 7.3% higher efficiency and a 20% lower rate of destruction exergy than the atmospheric hybrid system [8]. In a pressurized SOFC-GT hybrid system, the working fluid of SOFC is directly used in the turbine, resulting in less heat loss from the system; however, the operations of the two main subsystems between SOFC and GT are related and rather complicated. Due to the different operations of the two units, the SOFC-GT hybrid system has been studied in various ways. Chinda and Brault [9] found that the SOFC-GT system performance is limited by the cell temperature, the turbine inlet temperature, and the exhaust temperature, and the air mass flow rate for the system affects the variation of the heat exchanger properties. Bakalis and Stamatis [10] studied the operating parameters of the SOFC-GT hybrid system based on a SOFC scheme without any modification, i.e., optimum compressor and turbine geometries used to find the desired operating parameters for high system efficiency. Additionally, the matched operating condition of the two main units for the SOFC-GT hybrid system should be considered the limit of safe operation. Song et al. [11] investigated the SOFC-GT hybrid system considering the maximum allowable cell temperature. Bakalis and Stamatis [12] studied an SOFC coupled with microturbines. The limit of operating conditions is considered for parametric analysis to avoid system malfunctions. The proper design and management of the heat recovery are important to the performance of the hybrid system. Barelli et al. [13] studied heat recovery from the turbine exhaust gas used to heat the air inlet of SOFC, producing steam and heating for the steam reformer, by a recuperative heat exchanger. The thermal power loss for the recuperative heat exchanger is 10%.

The recirculation of SOFC exhaust gases affects the heat management within the system. Our previous work [14] showed that the recirculation of anode exhaust gas can increase the system efficiency for an SOFC system integrated with an ethanol reformer process by reducing the heat input for the preheating steam used in the steam reformer. When considering an SOFC-GT hybrid system with the recirculation of cathode exhaust gas, this system can increase thermal efficiency and avoid a high-temperature heat exchanger, which is costly [15,16]. Thus, an SOFC-GT hybrid system with anode and cathode exhaust gas recycling systems is an interesting power system that can minimize the required heat input for the system and maximize the system efficiency. Jia et al. [17] compared the internal-reforming SOFC system with three gas recycling types, and the results indicated that the system with both anode and cathode recycling has the highest efficiency by approximately 52%. However, there are few studies that perform a detailed analysis of the influence of recirculation of both anode and cathode exhaust gas on the performance of SOFC-GT hybrid systems. The anode and cathode gas recirculation systems have a direct impact on the SOFC and gas turbine performance. Furthermore, they also affect the heat recovery within the hybrid system. To fully understand the effects of the anode and cathode off-gas recirculation on both the SOFC and gas turbine performances, a parametric analysis of the SOFC-GT hybrid system with the recirculation of anode and cathode exhaust gas should be investigated.

In this regard, the objective of this study is to investigate the effects of anode and cathode gas recirculation on the performance of an SOFC-GT hybrid system combined with an external ethanol steam reformer. The effects of matching design parameters between the operation of SOFC and GT for SOFC-GT systems with anode or/and cathode recirculation were investigated. To examine the effect of matching design parameters between two units on the performance of different hybrid systems, the fuel utilization factor and SOFC operating temperature, which directly affect the performance of the SOFC-GT hybrid system, were studied first. Next, the additional fuel and air supply to the combustor, which are needed to specify the turbine inlet temperature in the SOFC-GT hybrid system with the recirculation of cathode or/and anode exhaust gas, were also investigated.

2. Configuration of SOFC-GT systems

Fig. 1 shows the integrated systems of the ethanol reformer and SOFC with gas turbine cycles. Three SOFC system designs are considered: (1) SOFC-GT system with anode recirculation (AR), (2) SOFC-GT system with cathode recirculation (CR) and (3) SOFC-GT system with both the anode and cathode recirculation (ACR). Ethanol as a fuel is pumped, mixed with steam and reformed to synthesis gas in an external reformer. The synthesis gas with rich hydrogen is then sent to SOFC stack. Since an exhaust gas at the anode of SOFC is composed of residual fuel and steam, which can be used for the reforming of ethanol, a portion of the exhaust gas can be recycled to the external steam reformer. This configuration is known as the SOFC-GT system with the anode recirculation. The remaining anode exhaust gas is mixed with an outlet oxidant gas from the cathode in a combustor. The combustion gas goes through a high-temperature heat exchanger before it is fed to a turbine to produce electricity. The exiting gas from the turbine is sent to a recuperator to preheat a compressed air. For the hybrid SOFC-GT system with the cathode recirculation, a portion of the cathode exhaust gas is recycled and mixed with a fresh air from the recuperator and then sent to the SOFC. The SOFC-GT system with both the anode and cathode recirculation is similar to that with the cathode recirculation but includes the anode recirculation (dash line in Fig 1b).

3. Model of the SOFC-GT hybrid system

A mathematical model is implemented to evaluate the system performance. This work focuses on the study of the configuration design in an SOFC-GT hybrid system. The mathematical models of the SOFC, gas turbine, and auxiliary units are derived from mass and energy balances under steady-state operation. The main assumptions used for the simulation of system behavior are as follows:

(1) All gases are considered as ideal gases.
(2) Pressure drops in the SOFC are negligible.
(3) Cathode and anode outlet temperatures are equal.
(4) The SOFC model is considered as a one-dimensional variation of parameters in the x-direction, and other components in the system are taken as a lumped control volume.
(5) Heat losses to the environment are negligible.

3.1. SOFC

The electricity from the SOFC is produced by the electrochemical reaction between hydrogen and oxygen. In the air channel, oxygen is reduced into oxygen ions. Then, the oxygen ions pass through the electrolyte to the anode/electrolyte interface. Hydrogen in the fuel channel reacts with oxygen ions, producing water and electrons at the anode side. The electrons flow from the anode side to the cathode side, generating electricity. The electrochemical reaction is as follows:

$$\text{Oxygen reduction reaction: } 1/2O_2 + 2e^- \rightarrow O^{2-} \quad (1)$$