Energy Conversion and Management 76 (2013) 571–580

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance analysis of hybrid solid oxide fuel cell and gas turbine cycle: Application of alternative fuels

Farshid Zabihian [a,*], Alan S. Fung [b]

[a] Department of Mechanical Engineering, West Virginia University, Institute of Technology, 405 Fayette Pike, Montgomery, WV 25136-2436, United States
[b] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada

ARTICLE INFO

Article history:
Received 16 April 2013
Accepted 2 August 2013

Keywords:
Solid oxide fuel cell
Gas turbine
SOFC–GT
Alternative fuels
Syngas

ABSTRACT

In this paper, the hybrid solid oxide fuel cell (SOFC) and gas turbine (GT) model was applied to investigate the effects of the inlet fuel type and composition on the performance of the cycle. This type of analysis is vital for the real world utilization of manufactured fuels in the hybrid SOFC–GT system due to the fact that these fuel compositions depends on the type of material that is processed, the fuel production process, and process control parameters. In the first part of this paper, it is shown that the results of a limited number of studies on the utilization of non-conventional fuels have been published in the open literature. However, further studies are required in this area to investigate all aspects of the issue for different configurations and assumptions. Then, the results of the simulation of the syngas-fueled hybrid SOFC–GT cycle are employed to explain the variation of the stream properties throughout the cycle. This analysis can be very helpful in understanding cycle internal working and can provide some interesting insights to the system operation. Then, the detailed information of the operation of the methane-fueled SOFC–GT cycle is presented. For both syngas- and methane-fueled cycles, the operating conditions of the equipment are presented and compared. Moreover, the comparison of the characteristics of the system when it is operated with two different schemes to provide the required steam for the cycle, with anode recirculation and with an external source of water, provides some interesting insights to the system operation. For instance, it was shown that although the physical configuration of the cycle in two systems is the same, the actual configuration (the equipment actually taking part in the process) can be different. Finally, the results of the simulation for different types of the inlet fuel show that system outputs and operational parameters are greatly influenced by changes in the fuel type. Therefore, the possibility of variation of the inlet fuel type should be considered, and its impacts should be investigated before utilization of biogas, gasified biomass, and syngas as fuel in hybrid SOFC–GT cycles.

1. Introduction

Although the utilization of renewable and alternative fuels has been very popular recently due to their environmental benefits and/or their renewable nature, their applications have been associated with some drawbacks. These drawbacks, especially when they are used to fuel fuel cell-based systems, should be studied and addressed before their widespread applications can be secured. One of the main problems that requires special attention is the variation of inlet fuel composition. Unlike gaseous fossil fuels such as natural gas, alternative fuels are produced by processing of feed stocks; therefore, their composition and quality vary with operating parameters of the process as well as the type of feed stock. For instance, in the cases of biogas and syngas, the type of biomass or coal that is processed can change the composition and quality of the produced fuels. Also, the fuel production process and process control parameters can affect the produced fuels. For example, both biomass and coal syngas are traditionally produced by the gasification process, where the fuel composition heavily depends on the gasifying agent, namely, steam, air, or oxygen. The fuel produced by this process mainly contains methane, hydrogen, carbon dioxide, water, nitrogen, and carbon monoxide; however, the concentration of each component depends on the gasifying agent and process control parameters. For example, in the oxygen, air, and steam-blown gasification processes, carbon monoxide/carbon dioxide, nitrogen, and steam can be found high in concentration, respectively [6,12,15]. Thus, the composition of alternative fuels can be altered and this problem should be addressed to identify the effects of variation in fuel composition on the system's overall performance before these fuels can be used in hybrid solid oxide fuel cell (SOFC) cycles.

In most published papers on hybrid SOFC system modeling in the open literature, methane or natural gas has been used to fuel the system. However, there are limited numerical studies that

* Corresponding author. Tel.: +1 (304) 442 3280.
E-mail addresses: farshid.zabihian@mail.wvu.edu (F. Zabihian), alanfung@ryerson.ca (A.S. Fung).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.08.005

Nomenclature

CHP	combined heat and power
GT	gas turbine
HHV	higher heating value
IGCC	integrated gasification combined cycle
LHV	lower heating value
MCFC	molten carbonate fuel cells
MGT	micro gas turbine
SCR	steam-to-carbon ratio
SOFC	solid oxide fuel cells
STP	standard temperature and pressure
TIT	turbine inlet temperature

investigated utilization of non-conventional fuels. Lobachyov and Richter [5], in one of the earliest numerical works in the field, developed a model that incorporated a coal gasification process into a hybrid SOFC–gas turbine (GT) cycle. Similarly, Kivisaari et al. [3] conducted a feasibility study to integrate a molten carbonate fuel cells (MCFC) or SOFC to a coal gasification plant in a combined heat and power (CHP) plant. Kuchonthara et al. [4] modeled the integrated power generation cycle combining thermochemical recuperation, brown coal gasification, and an SOFC. Rao et al. [8] compared an integrated gasification SOFC and an integrated gasification combined cycle (IGCC) in their thermoeconomic analysis. Van herle et al. [16] conducted an energy balance analysis on an existing biogas production unit integrated into an SOFC cycle in a small CHP system. Sucipta et al. [10] further investigated the gasification system integrated to an SOFC–micro gas turbine (MGT) cycle by adding and comparing different biomass gasification processes, namely, air, oxygen, and steam-blown. Using the same model, Sucipta et al. [11] studied the efficiency and temperature distributions in cases where natural gas, the normal fuel of the hybrid system, was mixed or completely replaced by biofuel. They investigated effects of composition changes on the performance of the SOFC–MGT hybrid system. They found that the efficiencies of the SOFC module and of the hybrid system noticeably decreased when natural gas was completely replaced by biofuel but the SOFC–MGT hybrid system could still be operated with reasonable performance. A more detailed review of these papers can be found elsewhere [18].

In this study, the model described in Suther et al. [13], and Suther et al. [14] was applied to observe the performance parameters of the hybrid SOFC–GT cycle with two configurations, with and without anode recirculation, when the system was fueled by syngas, methane, and other alternative fuels, including various forms of biogas and gasified biomass. The methodology, mathematical formulation, assumptions and simplifications, model constants and parameters, and model validation for the SOFC part of the model and hybrid SOFC–GT were presented elsewhere [13,14]. The models were developed using Aspen Plus® platform. In order to monitor the performance of the system, stream parameters such as temperature, pressure, flow rate (mass, volume, and molar), and composition of flows were considered. For the equipment, their characteristics, such as power, specific work, efficiency, and heat duty were investigated.

This paper starts with the analysis of the syngas fueled hybrid SOFC–GT cycle, including thermodynamic properties of all major streams in the cycle and operational conditions of all main equipment. Then, the same analysis is presented for methane-fueled system and the results are compared with the results of the system fueled with syngas. Finally, the system performance is evaluated when it is fueled by natural gas and various forms of biogas and gasified biomass with different compositions.

2. Variation of operational parameters throughout the cycle in the syngas-fueled hybrid SOFC–GT system

In the first part of this paper, all important properties, such as temperature; pressure; mass, volume, and molar flow rates; lower and higher heating values; and composition of all major streams in the syngas-fueled hybrid SOFC–GT cycle are investigated for two configurations: cycle with and without anode recirculation. In addition, operational conditions, like output power, specific work, efficiency, and heat duty of all equipment, such as SOFC stack, GT, fuel reformer, compressors, heat exchangers, and pump are evaluated. This analysis can help in better understanding of the hybrid SOFC–GT cycle inner workings. The composition of syngas used in this work is listed in Table 1 [2].

To explain the inner working of the system, the air and fuel flows are followed and all major processes are investigated (Tables 2 and 4). Fig. 1 illustrates the model configuration of the cycle under investigation. In this figure, the streams are numbered to facilitate explanation. It should be noted that Fig. 1 depicts the general configuration of the cycle. When the cycle with anode recirculation is under investigation, the flow rate of stream 22 (external water stream) is zero and when the cycle without anode recirculation is modeled, the flow rate of stream 14 (anode recirculation stream) is zero. Discussion is first presented for cycle with anode recirculation. Then, major differences for the cycle without anode recirculation are explained. Tables 3 and 5 show the power, specific work, and efficiency of mechanical systems for cycles with and without anode recirculation, respectively. Also, the heat duty of various heat exchangers can be seen in Table 6 for both configurations.

In order to explain the system with anode recirculation, the fuel flow is followed first. Fixed amount of fuel, 20 kg/h, stream 6, enters to the cycle at standard temperature and pressure (STP) and is pressurized at the fuel compressor to 3 bar (stream 7). The temperature and pressure of the inlet fuel before entering the compressor are 25 °C and 1 bar, respectively. Also, the lower and higher heating values of the fuel are 12,658 and 13,376 kJ/kg, respectively. The power required for this compression is about 1 kW at 85% efficiency, and the temperature of the stream at the outlet of the fuel compressor is 152 °C. Stream 7 is heated at the heat exchanger (FHX), and its temperature increases to 219 °C. The heat duty of this heat exchanger is 0.6 kW. Stream 8 then mixes with the recycled part of the anode exhaust (stream 14) before entering the reformer. Within the reformer two reactions take place (Equations 1 and 2):

$$CH_4 + H_2O + \text{heat} \leftrightarrow 3H_2 + CO \quad (1)$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 + heat \quad (2)$$

Table 1
Molar composition of a syngas used in this analysis [2].

Fuel type	Syngas (dry coal feed)
Composition (%)	
CH_4	1.4
H_2	30.0
CO_2	1.6
CO	60.3
H_2O	2.0
N_2	4.7