Journal of the Energy Institute 87 (2014) 18–27

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Performance analysis of hybrid solid oxide fuel cell and gas turbine cycle (part I): Effects of fuel composition on output power

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ARTICLE INFO

Article history:
Received 17 July 2012
Accepted 29 April 2013
Available online 18 February 2014

Keywords:
Solid oxide fuel cell
Gas turbine
SOFC–GT
Fuel composition
Output power

ABSTRACT

In this paper, the model of hybrid solid oxide fuel cell (SOFC) and gas turbine (GT) cycle is applied to investigate the effects of the inlet fuel type and composition on the performance of the hybrid SOFC–GT cycle. The sensitivity analyses of the impacts of the concentration of the different components, namely, methane, hydrogen, carbon dioxide, carbon monoxide, and nitrogen, in the inlet fuel on the performance of the hybrid SOFC–GT cycle are performed. The simulation results are presented with respect to a reference case, when the system is fueled by pure methane. Then, the performance of the hybrid SOFC–GT system when methane is partially replaced by each component within a corresponding range of concentration with an increment of 5% at each step is investigated. The results point out that the output powers of the SOFC, GT, and cycle as a whole decrease sharply when methane is replaced with other species in majority of the cases.

1. Introduction

One of the advantages of hybrid solid oxide fuel cell (SOFC) cycles in comparison to other fuel cell systems is their fuel flexibility. Different fuels with a wide range of properties and composition have been adopted for hybrid SOFC system modeling in the open literature [1]. However, the analysis of the effects of variation in the fuel composition on the performance of the SOFC–gas turbine (GT) cycle is scarce in the literature. In one study, Van herle et al. (2003) evaluated efficiencies of an SOFC (electrical efficiency) and combined heat and power (CHP) system (total efficiency) in a biogas production plant integrated with an SOFC in a CHP plant as a function of the CO_2 fraction in the biogas feed in a range of 20%–65% [2].

In a more comprehensive study, in 2008, Sucipta et al. (2008) published their research on a biomass fueled hybrid SOFC–micro gas turbine (MGT) cycle [3]. They evaluated the effects of biomass fuel chemical species composition, namely, H_2, CO, CO_2, H_2O, and N_2 on the system performance parameters. In order to evaluate system performance, they considered voltage, electric current, power, efficiency, distributions of temperature in the SOFC, and distributions of mole fractions of participating chemical species in the internal reformer. They found that change of H_2O and H_2 concentration in the fuel from 0% to 50% slightly reduced the efficiency of the hybrid system. Changes in the hybrid system performance and in all studied parameters were similar between the two cases. Changes of N_2 concentration resulted in a slight decrease of efficiency both for the SOFC module and for the hybrid system. On the other hand, an increase of the CO concentration produced similar effects as that of CO_2 concentration and resulted in a decrease of the efficiency of both the SOFC module and hybrid system significantly. Sucipta et al. (2007) further investigated the gasification system integrated to an SOFC–MGT cycle by adding and comparing different biomass gasification processes, namely, air-blown, oxygen-blown, and steam-blown gasification processes [4]. Using the same model, Sucipta et al. (2008) 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 [5]. They investigated effects of composition changes on the performance of the SOFC–

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http://dx.doi.org/10.1016/j.joei.2014.02.002

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.

In this work, the model described in Suther et al. (2010, 2011) is applied to observe the effects of fuel composition on the performance of the hybrid SOFC–GT cycle with two configurations: with and without anode recirculation [6,7]. Fig. 1 illustrates the configuration of the cycle under investigation.

In the SOFC–GT cycle model, the inlet fuel to the system is first compressed from standard temperature and pressure (STP) to system pressure (at F-COMP), and its temperature is increased at FHX by heat recovered from the GT exhaust. In order to provide required water for the fuel reforming reactions, and to prevent coking in the reformer and SOFC stack, in the cycle with anode recirculation, the fuel is mixed with the recycled part of the anode off-gas stream in a mixer (AN-MIXER). The mixture of fuel and anode exhaust recirculation, containing enough steam for the fuel reforming process, is then fed to the fuel pre-reformer (REFORMER).

The fuel reforming reactions are endothermic. In order to provide required heat, the excess heat released by the SOFC stack is first exchanged with the reformer and then with the incoming air (at AIR HE) and finally discharged to the environment. The reformer outlet is heated to SOFC operating temperature at FHX2, if its temperature is not high enough, before it is fed to the SOFC anode at AN-IN.

The inlet air, entering the system at STP, is compressed at A-COMP and heated at AIR HE and AHX by the excess heat extracted from the SOFC and the gas turbine exhaust, respectively. If the temperature at the AHX outlet is lower than the SOFC operating temperature, the air is heated by the high energy COMB-OUT stream at AHX2 before being fed to the SOFC cathode at CAT-IN. The fuel and air, entering the SOFC at the anode and cathode, respectively, participate in the electrochemical and reforming reactions producing electrical work and releasing heat. The anode off-gas is split into two streams at AN-SPLT. Since anode exhaust contains a high percentage of steam, part of this stream is recycled to mix with the fuel.

The rest of the anode exhaust stream (unrecycled part of AN-OUT) is burnt with the cathode exhaust stream (CAT-OUT) at the GT combustor. The combustor outlet, after passing through AHX2 and FHX2, enters the gas turbine. The turbine inlet temperature (TIT) is a critical parameter in GT operation and should not exceed a certain limit. In the model, in order to achieve the user-defined TIT, the air-to-fuel ratio of the system was automatically adjusted for constant fuel flow rate. Finally, in the cycle, the GT exhaust is used to heat the inlet fuel in AHX and FHX.

The model can simulate two cycle configurations, with anode off-gas recirculation and with heat recovery steam generator (HRSG) to provide steam for the reforming reaction. Thus far, the cycle with anode off-gas recirculation has been explained. By enabling or disabling the anode exhaust recirculation feature, both cycles can be studied. If the anode recycling is disabled; steam provided by the HRSG (WHX) is mixed with the fuel to meet the required steam for fuel reforming reactions.

In order to monitor the performance of the system, parameters such as SOFC and system thermal efficiencies; net and specific work of SOFC, GT, and cycle; air-to-fuel ratio; air and fuel mass flow rate, and so on are investigated. In order to perform the analyses, the reference case is introduced when the hybrid SOFC–GT system is fueled by pure methane. Then, discussion of the cases where methane is partially replaced by H_2, CO_2, CO, and N_2, the chemical species that can be found in fuels, is developed. This Part I of the presentation deals with the

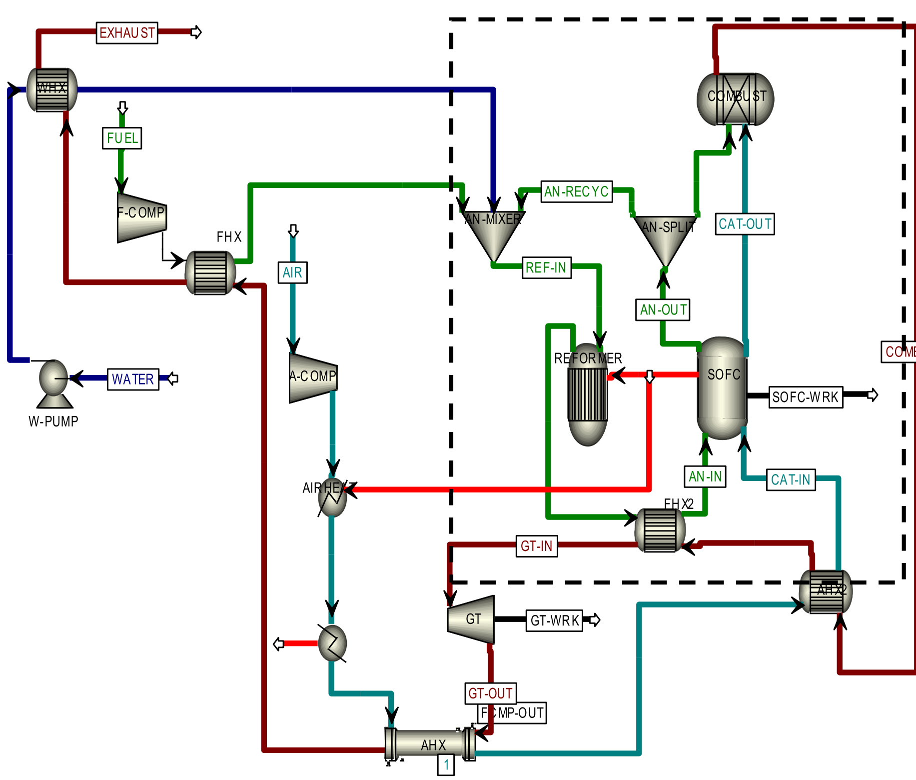

Fig. 1. Hybrid SOFC–GT cycle configuration.