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Original Research Article

Thermodynamic sensitivity analysis of hybrid system based on solid oxide fuel cell

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ABSTRACT

This paper is focused on the steady-state performance of a hybrid solid oxide fuel cell (SOFC)-gas turbine (GT) cycle. First, the model of the hybrid SOFC-GT cycle is developed and then the model is used to perform a series of sensitivity analyses to investigate the impact of various design and operating parameters on the performance of the cycle without anode recirculation when the system is fuelled with methane. The following system operating and design parameters are investigated: SOFC operating temperature, fuel utilization factor, current density; system operating pressure; turbine inlet temperature (TIT); and isentropic efficiency of the GT. The system performance is monitored by recording and evaluating the specific work of the SOFC, GT, and system as a whole; SOFC-to-GT work ratio; and cycle efficiency (based on the LHV). The results of the modeling illustrated that the cycle efficiency can be improved by increasing system operating pressure, SOFC operating temperature, and GT isentropic efficiency and decreasing SOFC current density and TIT. Also, it is shown that increasing system operating pressure, fuel utilization factor, and TIT can positively affect cycle net specific work, while increasing SOFC operating temperature and SOFC current density has negative impact on the cycle net specific work. The influence of the fuel utilization factor on the cycle efficiency depends on the GT isentropic efficiency.

Introduction

Solid oxide fuel cell-based systems are one of the main candidates for future sustainable power generation. Hybrid solid oxide fuel cell (SOFC) and gas turbine (GT) cycles are the most commonly numerically studied system and the only one studied experimentally among several proposed systems [1]. In hybrid SOFC-GT systems, the high temperature outlet stream of the fuel cell containing high concentration of thermal energy is used to run a gas turbine. This system can also be explained as a Bryton cycle where the combustor is replaced with the SOFC unit.

Fuel cell hybrid systems commonly consist of various SOFC stacks with different configurations, gas turbines, fuel and air compressors, heat exchangers, anode recirculation, a water pump, heat recovery steam generators, pre-reformers, internal reformers, mixers, (catalytic) burners, bypasses, electric generators, and invertors. Although the layouts of these cycles are relatively simple due to their limited components, the interactions among these components are very complicated. In order to understand the behavior of these systems, many parameters should be investigated. The parametric analyses of the SOFC-GT cycles can help to understand operation of the systems and can provide an insight to the optimization of the system configuration and operating parameters. Several studies in the literature presented parametric analyses of the SOFC-based cycles e.g. Chinda and Brault [2], Bao et al. [3], and Pirkandi et al. [4].

Trasino et al. [5] developed a model of a 1 MW hybrid SOFC-GT system consisting of a two stage turbogenerator and an internal reforming SOFC. The system layout included anode and cathode off-gas recirculations. The anode exhaust stream was recycled to provide steam required for the fuel reforming and to preheat the inlet fuel. Similarly, the cathode exhaust stream was recycled to preheat the air inlet stream. They studied design and off-design performance of the cycle. They investigated the effects of ambient temperature, on the system efficiency, SOFC inlet pressure, power output, and fuel utilization factor at full load and part loads operation of the system. They concluded that their results provided an operating envelope that can ensure proper operation of the system as whole and its components as well as an optimum efficiency.

Jia et al. [6] numerically studied hybrid SOFC-GT power system fueled with methane and compared it with other SOFC-based

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power systems. They reported the electrical efficiency of 61% and cogeneration efficiency of 80% for the system.

Calise et al. [7] studied the effects of current density, system operating pressure, fuel-to-oxygen ratio, water-to-methane ratio, and fuel utilization factor on the efficiency of a hybrid SOFC-GT system. They found that increasing the fuel utilization factor improved the efficiency of the cycle, while the impact of steam-to-carbon ratio was not favorable.

Chan et al. [8,9] developed a model of a hybrid SOFC-GT-CHP system with the electrical and total efficiencies of over 62% and 83%, respectively. They investigated the effects of system operating pressure and fuel flow rate on the system overall performance through the first law of thermodynamics analysis on the model.

Palsson et al. [10] developed a finite volume model of a 500 kW hybrid SOFC-GT system using a 2-D model of a planar electrolyte-supported SOFC. They studied various system parameters, including the electrical efficiency, specific work, turbine inlet temperature (TIT), and SOFC temperature with respect to the compressor pressure ratio and inlet air flow rate. They found that increasing TIT did not improve system efficiency and specific work. Unlike TIT, they showed that the system operating pressure had great impact on hybrid system performance.

In the following sections, the configuration of the hybrid SOFC-GT cycle under investigation in this paper is presented. Then, the impact of various operating parameters on the performance of the cycle is investigated.

Hybrid SOFC-GT cycle model

In this section only the development of the hybrid SOFC-GT model is explained. The methodology, mathematical formulation, assumptions and simplifications, model constants and parameters, and model validation for the SOFC part of the model were presented elsewhere [11,12].

The SOFC Fortran model, developed based on the description presented in Suther et al. [11], was integrated into a hybrid SOFC-GT cycle model in Aspen Plus®. During the execution of the hybrid cycle model, when the SOFC stack was encountered, the SOFC model was called. For the execution of the SOFC stack as a stand-alone model, the flow rates of the fuel and air, the composition of the fuel, and the operating temperature and pressure of the SOFC must be specified by the user. When the model was executed within the hybrid cycle model, the flow rates and composition of the streams entering the SOFC were fed to the SOFC model based on the calculation of the hybrid model configuration and operating parameters in Aspen Plus®. The user also needed to input several thermodynamic and electrochemical parameters and constants to complete the calculations of the hybrid SOFC-GT model. The hybrid cycle model required thermodynamic models for the compressors, gas turbine, fuel reformer, combustor, material stream mixers and splitters, and heat exchangers. Built-in models of Aspen Plus® were used to model these components.

The hybrid SOFC-GT model was developed considering the following general assumptions and considerations:

- The inlet fuel to the cycle was a mixture of gases, which consisted of any combination of CH_4, H_2, H_2O, CO, CO_2, O_2, and N_2, which means the inlet fuel was sulfur free and no desulfurization equipment was required. The inlet fuel was delivered to the system at ambient temperature and pressure.
- The air supplied to the fuel cell could be comprised of any combination of O_2, N_2, CO_2, and H_2O. For this study, the composition of air was 21% O_2 and 79% N_2.
- Chemical components behaved as ideal gases at the operating temperature and pressure of the cycle (similar to [13,14]).
- No pressure losses occurred within the equipment (similar to [7,10,15]). It should be noted that in order to consider pressure losses, some preliminary information about system physical configuration and its dimensions is required. However, in this work the objective was to develop a thermodynamic model of the system. Therefore, the pressure drop of the components was out of the scope of this work.
- The fuel reformer considered methane steam reforming and water–gas shift reactions at chemical equilibrium.
- The fuel reformer and SOFC were designed such that the heat produced by the SOFC could be utilized in the fuel reformer.
- There were no heat losses in the equipment (similar to [7,13,16–18]).
- The mechanical losses of turbomachinery and DC/AC convertor losses were neglected.

System configurations

The basic configuration of the hybrid SOFC-GT cycle investigated in this research is shown in Fig. 1. This figure shows the model components in the Aspen Plus® model. Although the model can simulate the system with two operation modes, i.e. with or without anode exhaust recirculation, this figure only shows the system without anode exhaust recirculation which is the subject of this paper. The equipment models encircled by the dashed line represent the SOFC stack and its internal components. Fig. 2 illustrates a schematic diagram of an actual SOFC module [19]. The model components encircled by the dashed line in Fig. 1 can be compared with Fig. 2 to find how each component in the model corresponds to the equipment in the real system. This comparison shows that the model configuration and the real system resemble each other, and this is one of the distinguishing points between this work and most other modeling works in the literature. Table 1 shows the temperature, pressure, and mass flow rate of all streams in the base case.

In the model, the inlet fuel is first compressed at F-COMP from standard temperature and pressure (STP) to the system pressure. Then, the compressed fuel is heated at FHX by heat recovered from the GT exhaust. It should be noted that in real systems, natural gas is normally delivered to the system at high pressure and ambient temperature. Some models in the literature, such as Massardo and Lubelli [20], considered these conditions (natural gas inlet at high pressure and ambient temperature). Assuming that the inlet natural gas is at ambient pressure and temperature, two major differences between the model and the real system can result: some work must be consumed in the compressor to pressurize the stream and as a result the temperature of the stream significantly increases. However, the assumption of the inlet fuel at ambient temperature and pressure is common in the literature and is consistent with many modeling works on the natural gas fuelled power generation systems [21,22].

In order to provide required steam for the fuel reforming reactions, and to prevent coking in the reformer and SOFC stack, steam provided by the heat recovery steam generator (HRSG), WHX, is mixed with the fuel to meet the required steam-to-carbon ratio (SCR) of the fuel reforming reactions. The HRSG flow rate is dependent on the molar flow rate of carbon at the inlet fuel and the user-defined SCR and was estimated by the following equation:

$$\dot{n}_{H_2O,HRSG} = SCR \times \dot{n}_{C,fuel} \tag{1}$$

where $\dot{n}_{H_2O,HRSG}$ is the molar flow rate of the water inlet to the HRSG.