Energy, Exergy and Thermoeconomic Analysis of the Novel Combined Cycle of Solid Oxide Fuel Cell (SOFC) and Biogas Steam Reforming (BSR) for Cogeneration Power and Hydrogen

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ABSTRACT

In this paper, a new configuration of a solid oxide fuel cell / gas turbine (SOFC/GT) combined cycle system with biogas reforming cycle is presented for the purpose of coproduction production of power and hydrogen. The heat output from the base system of the SOFC/GT is used to supply the energy required for the reforming reaction and to drive the biogas reforming cycle for hydrogen production. Comprehensive thermodynamic and thermoeconomic modeling has been performed using EES Software. Also, the parametric study has been analyzed for the effect of different parameters on the net output power, energy and exergy efficiency, exergy destruction rate and the Sum Unit Cost products (SUCP) of the whole system. The results show that the energy efficiency and exergy efficiency of the proposed combined system have increased comparison the SOFC/GT system by 23.31% and 28.19%, respectively. The net output power and hydrogen production rate are obtained 2726 kW and 0.07453 kg/s, respectively. From the exergy viewpoint, the afterburner causes a considerable amount of exergy destruction for the system by approximately 26% of the total exergy destruction rate. By increasing the inlet temperature fuel cell, the cell voltage reaches a maximum value at a temperature of 679 K and then decreases. As a result, energy and exergy efficiency are maximized and then reduced. Besides, the total exergy destruction rate and SUCP of the cogeneration system is calculated equels to 1532 kW and 9400 $/GJ, respectively.

KEYWORDS

Cogeneration system, Oxide fuel cell, Steam reforming, Energy and Exergy.

1. Introduction

Increasingly energy consumption, due to the rapid development of commercial divisions and population increase, was amplified substantially in recent years [1]. Accordingly, to address the further required power, various plants were conspicuously developed [2]. However, these power plants utilize fossil fuel resources that produce greenhouse gas emissions like Carbone dioxide, resulting in Ozone layer diminution and global warming. Consequently, some restrictions, such as enacting the Kyoto and Montreal protocols, were taken into account to reduce air contamination [3]. In this regard, the development of renewable energy resources attracted attention globally. Thus, fuel cells and the hydrogen industry can address multiple problems that arise with conventional energy conversion systems.

Since solid oxide fuel cells operate in normal pressure conditions, high-pressure SOFCs can be utilized to produce high-temperature exhaust gases that can be further delivered to gas turbines for producing electricity. In combined SOFC-GT cycles, the exhaust gases of SOFC are directly inserted into the gas turbine in a high-pressure and high-temperature state. Campanari et al. [4] showed that the integration of a solid oxide fuel cell with a gas turbine has a relatively higher efficiency than the combined cycle of a steam turbine. However, they report an ultimate efficiency of more than 75% for both systems, while whiston et al. [5] reported an electric efficiency of 9.52% for the same gas turbine combined cycle.

The utilization of biogas to generate hydrogen based on the reforming processes has become an attractive technology for small-scale locally distributed units. In the biogas CH_4 and CO_2 are the basic elements, where the dry reforming process can be the most appropriate option to generate hydrogen [6]. Among various processes, steam methane reforming (SMR) is the most prevalent chemical process in converting methane into hydrogen with water to methane ratio of 1:1. A biogas steam reforming system is proposed by Cipiti et al. [6] in a temperature range of 700- 900 ^{o}C, where theoretical and empirical studies are performed. Based on their results, the increment of the temperature and steam-to-carbon molar ratio can improve the hydrogen generation rate.

2. Methodology

Comprehensive thermodynamic and thermoeconomic modeling has been performed using EES software. Also, a parametric study has been performed to demonstrate the effect of different parameters on the main performance metrics of the devised system.

3. Results and Discussion

In this part, the obtained results of the energy, exergy, and exergoeconomic analyses for the devised SOFC-GT-BSR are presented based on the design conditions, assumptions, and governing equations.

It consists of two major subsystems, each of which is validated separately with the related publication. Therefore, the obtained results of the SOFC unit is compared with the work of Sadat et al. [7] and Ma et al. [8] . It can be seen that there is a good agreement in the present work with the mentioned reference. Also, the data acquired by Ma et al. [8] were used to assure the validity of the obtained data for the SOFC simulation. The comparisons of voltage variation as well as the power density between the present study and the one conducted by Ma et al. are depicted in Fig. 2. In these comparisons, the SOFC inlet pressure is considered to be equal to that of ambient pressure. It is evident that an acceptable agreement is witnessed.

Furthermore, the main results of the SOFC-GT-BSR system are presented that shows the energy efficiency of the hybrid SOFC-GT-BSR system is improved from 52/28% to 64/47% compared to stand-alone SOFC-GT unit; thus, from the first-law viewpoint, the integrated system provides competent results. Moreover, the exergy efficiency of the proposed combined system can be enhanced from 50/43% to 64/65%, which indicates that the combination of systems provides higher exergetic efficiency rather than stand-alone systems. Besides, SOFC electrical power, net output electrical power, and hydrogen mass flow rate are obtained 2424 kW, 2726 kW, and 0/07453 kg/s, respectively. Furthermore, the total exergy destruction rate and SUCP of the cogeneration system is calculated as 1532 kW and 9400 $/GJ, respectively. The highest exergy destruction rate among all components of the system belongs to afterburner with a rate of 404/8 kW followed by gas turbine and SOFC stack with values of 302/6 kW and 158/7 kW, respectively. Also, the effect of major operating parameters such as current density, SOFC inlet temperature, carbon dioxide to methane molar ratio, steam to carbon molar ratio, and reformer temperature on the performance of the SOFC-GT-BSR integration is analyzed to provide a better understanding of system's performance.

4. Conclusion

In the present work, a combined system based on a combination of solid oxide fuel cell (SOFC) with biogas-steam reformer (BSR) driven by renewable energy resources (CH_4 and $CH_4 + CO_2$) was investigated from the energy, exergy, and exergoeconomic perspective. The major goal of this system is to recover the wasted energy of SOFC-GT for hydrogen production within the BSR system with the minimum environmental effects. A precise model of the reference concept was developed employing Engineering Equation Solver (EES). Based on the developed model, the detailed thermodynamic and economic analysis were performed. Also, the parametric study of the hybrid system has been performed to investigate the effect of different parameters on the target functions, which include SOFC voltage, net output power, energy and exergy efficiency of SOFC and combined system, hydrogen mass flow rate and the Sum Unit Cost of products (SUCP) of the whole system and among the examined parameters, SOFC inlet temperature and compressor pressure ratio are the most important parameters that affect the performance of the SOFC and BSR units. In this regard, the significant results are listed as follows:

- The energy efficiency of the hybrid SOFC and BSR system is improved by 23/31% from 52/28% to 64/47% compared to the stand-alone SOFC-GT unit.

- The exergy efficiency of the combined SOFC and BSR system can be enhanced by 28/19% from 50/43% to 64/65% ,which indicates that the combination of systems provides higher exergetic efficiency rather than stand-alone SOFC-GT system.

- SOFC electrical power, net output power, and hydrogen mass flow rate are computed as 2424 kW, 2726 kW, 0/07453 kg/s, respectively.
- Afterburner contributed to the highest exergy destruction rate among all components of the system with a rate of 404/8 kW followed by gas turbine and SOFC stack with values of 302/6 kW and 158/7 kW, respectively.

- The highest rate of exergy destruction cost belongs to the gas turbine by 310558 $/year.

- The net output power system increases to approximately 4340 kW by increasing the current density and then decreases. Also, the SUCP of the system decreases at the approximate current density of 14143 A/m^2 and then increases.

- The SUCP of the system increases to approximately 9420 $/GJ at PR=12 and then decreases with the increment of the compressor ratio.

- By increasing the inlet temperature of the fuel cell, the SOFC voltage at the approximate temperature of 679 K reaches the maximum value and then decreases; as a result, the energy and exergy efficiencies increase to the highest point and then drops. Also, the SUCP of the system reaches the minimum amount of 9240 $\$/GJ$ and then increases.

5. References

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