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Thermodynamic and exergoeconomic assessments of a new solid oxide fuel cell-gas turbine cogeneration system

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ABSTRACT

A new indirect integration of a solid oxide fuel cell, a gas turbine and a domestic water heater is proposed and analyzed in detail. Using a proper working fluid for each subsystem, interacting thermally with one another, the proposed system generates power and hot water simultaneously. Thermodynamic and thermoeconomic principles are used to determine the products costs and the order of significance of system components from the viewpoint of exergy destruction. Parametric studies are carried out to reveal the influence on the system performance of several decisive parameters. The results show that the exergy efficiency is maximized at a compressor pressure ratio of 9.49 and a current density of 1642 A m^{-2}. The increase in pressure ratio however, is not in favor of system's economic performance. In addition, the sum of unit costs of the products is minimized at a current density of 1523 A m^{-2}. Moreover, it is shown that an increase in the gas turbine inlet temperature or steam to carbon ratio deteriorates both the thermodynamic and economic performances of the system. Furthermore, the results indicate that a higher fuel utilization factor improves the thermodynamic and economic behavior of the system. Finally, it is revealed that an increase in the gas turbine air flow rate enhances the energy efficiency and worsens the sum of unit costs of the products. The exergy efficiency however, is maximized at a gas turbine air flow rate of 15.94 mol s^{-1}.

1. Introduction

Energy is one of the most important requirements for a society's economical, industrial and political survival, development and activities. Great increase in fuel cost, negative environmental impacts such as greenhouse gas emission, global warming, acid rains and local air pollution caused by direct combustion, shortage of natural fuel resources and growing energy demand by developing countries have all made scientists to find new ways to convert chemical energy of a fuel into usable forms of energy like electrical power, cooling and heating. These new energy conversion systems should be sustainable, reliable, more efficient, more economical and environmental friendly with minimum side effects. Up to now a lot of efforts have been made to accomplish this aim. Considering the above-mentioned concerns, fuel cells can be a new appropriate candidate for energy extraction from fuels. Fuel cells are electrochemical devices that convert chemical energy of a fuel into electricity without direct combustion. Therefore, they do not have many limitations of the conventional combustion engines and hence can be more efficient with low noise and environmental emissions [1]. Among different types of fuel cells, solid oxide fuel cells (SOFCs) are the only ones that have a solid electrolyte. They have a high working temperature (600–1100 °C) which brings about several advantages for them. First of all they do not require noble metal catalysts so that their cost has the potential to become competitive in future. SOFCs can internally reform available fuels into hydrogen, which makes SOFCs more attractive. The gaseous hydrogen, natural gas, hydrocarbons, solid and liquid fuels, products of coal gasification and biomass can be used as fuels for SOFC. Due to the high operating temperature of SOFCs, their off-gases have large amounts of heat energy. This exhaust can be used to run some other systems like gas turbines (GTs) or for space or domestic water heating applications. Compared to the conventional power plants which converts only 30% of the fuel's available energy into electrical power the SOFC-based cogeneration system producing electrical power and cooling or heating can achieve an overall efficiency of above 70%. For these cogeneration systems environmental emissions (such as carbon dioxide) and also operation and maintenance costs are less than the corresponding values for separate heat and power producing systems [2].

As Zhang et al. [3] stated there are three major schemes for SOFC hybrid systems. In one of the schemes, known as direct integration, both systems operate with the same working fluid and at

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Nomenclature

A	heat transfer area (m^2)
$\dot{C}$	cost rate (\$ h^{-1})
$\bar{g}$	gibbs free energy (kJ $kmol^{-1}$)
$\bar{h}$	molar enthalpy (kJ $kmol^{-1}$)
LHV	lower heating value (kJ $kmol^{-1}$)
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (bar)
r_{sc}	steam to carbon ratio
PR	pressure ratio
$\bar{s}$	molar entropy (kJ $kmol^{-1}$ K^{-1})
T	temperature (K)
Z	capital cost of a component (\$)

Greek symbols

η	efficiency (%)
ε	effectiveness (%)

Subscripts

a	anode
c	cathode
e	electrode
f	fuel
int	interconnection

the same pressure level. In the indirect integration scheme the SOFC system and the bottoming cycle operate with different working fluids at different pressures and thermal energy is exchanged between them indirectly through heat exchangers. In the fuel coupling scheme a hydrogen production unit or a fuel reformer is integrated with the SOFC system.

If simplicity and reliability is mostly desired the indirect integration of SOFC-GT is appropriate. In this configuration, the fuel cell can operate at atmospheric pressure and the gas turbine can have a stable and high value of turbine inlet temperature, since the SOFC and GT operate independently. Furthermore, for this configuration some special types of fuels which cannot be tolerated by SOFC, or are potential source of faults for the gas turbine, can also be used. However, this design is less efficient and more expensive than the direct one [4]. The followings are some research works published in this regard:

Cheddie and Murray [5] proposed an indirect integration of solid oxide fuel cell with a 10 MW gas turbine plant. Based on the developed model they predicted that as a result of the coupling the thermal efficiency is increased from 30% to 48% and that the cost of power is reduced from 5.46 to 4.65 ¢ kW h^{-1}. Cheddie [6] optimized the thermoeconomic performance of the above-mentioned hybrid power plant using the Lagrange Multipliers method. The obtained results showed optimized maximum output power of 18.9 MW at an efficiency of 48.5% and a breakeven per-unit energy cost of 4.54 ¢ kW h^{-1}. Cheddie and Murray in another work [7] considered a semi-direct integration of solid oxide fuel cell and gas turbine. Thermoeconomic optimization revealed that for this system the best performance was achieved when 12 MW out of the 21.6 MW total power output is produced by the SOFC. Bicer and Dincer [8] proposed a system consisting of steam assisted gravity drainage, underground coal gasification, solid oxide fuel cell, integrated gasification combined cycle and an electrolyser. They calculated an energy and exergy efficiency of 19.6% and 17.3% for the overall system, respectively. Zhao et al. [9] studied a coal syngas fed atmospheric SOFC stack which is indirectly integrated into a Brayton cycle. They concluded that the system efficiency increases with decreasing current density and is between 48% and 56%, depending on the operating temperature and current density. Mathieu [10] integrated a high temperature SOFC in a near-zero emission regenerative E-MATIANT cycle and reported positive effects on the CO_2 removed from the system and the overall efficiency. Williams et al. [11] proposed an indirect combination of SOFC-GT. They showed that the maximum attainable efficiency for their system is 45% and that their scheme has lower efficiency than the direct combination of the two systems. Zhang et al. [12] proposed a new model for a SOFC-GT system. In this system the waste heat from SOFC stack as well as the combustion chamber is utilized to heat up the gas turbine inlet. They claimed that the hydrocarbons are feasible fuels for the SOFC. Eveloy et al. [13] investigated an indirect integration of gas turbine with an internal reforming SOFC system and an organic Rankine cycle (ORC) thermodynamically and economically. For toluene as the ORC working fluid, they reported that the SOFC-GT-ORC system exhibits an efficiency improvement of approximately 34% compared to the gas turbine as a stand-alone system, and of 6% compared to the hybrid SOFC-GT subsystem. They predicted that the system would become profitable within three to six years. Inui et al. [14] proposed a combination of SOFC and closed cycle magneto hydrodynamic (MHD)/noble gas turbine with carbon dioxide recovery. They reported that the overall thermal efficiency of the system using natural gas (methane) as the fuel reaches 63.66% (HHV) or 70.64% (LHV). Inui et al. [15] introduced two types of carbon dioxide recovering SOFC-GT combined power generation systems in which a gas turbine either with carbon dioxide recycle or with water vapor injection is adopted as the bottoming cycle. They reported that the overall efficiency of the system with carbon dioxide recycle reaches 63.87% (HHV) or 70.88% (LHV). These values for the system with water vapor injection reach 65.00% (HHV) or 72.13% (LHV). Sánchez et al. [16] compared the performances of conventional recuperative gas turbine with direct/indirect integration of the SOFC and GT systems at full and part load. They concluded that the indirect hybrid system is less efficient than the direct one since power and efficiency improvement caused by the higher pressure in the SOFC is not present in the indirect system. They also figured out that the total cost of a fuel-cell-based plant is lower in spite of the higher initial investment/installation cost of a hybrid system.

Although several different configurations of SOFC-GT system have been studied in recent years; to the authors' knowledge, the comprehensive thermodynamic and exergoeconomic analyses of an indirectly integrated SOFC-GT have not been performed yet. This work is an attempt to fulfill this lack of information.

In this paper a new indirect integration of SOFC-GT with heat cogeneration is proposed. This plant generates electrical power in the SOFC and GT components and uses off-gases waste heat to produce pressurized hot water for domestic use. For system evaluation, first an electrochemical analysis is performed for the fuel cell to calculate the output voltage and electrical power. Then the conservation of mass and energy, exergy balances and exergoeconomic relations are applied to each system component. Using the Engineering Equation Solver (EES) software, a parametric analysis is conducted to evaluate the effects on the thermodynamic and exergoeconomic performance of the system of major decisive parameters. It is expected that the results will be helpful in designing efficient SOFC-based cogeneration systems.