We are IntechOpen, the world’s leading publisher of Open Access books
Built by scientists, for scientists

6,600 Open access books available
177,000 International authors and editors
195M Downloads

154 Countries delivered to
TOP 1% Our authors are among the most cited scientists
12.2% Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com
Chapter

SOFC-Gas Turbine Hybrid Power Plant: Exergetic Study

Salha Faleh and Tahar Khir

Abstract

The combined solid oxide fuel cells and gas turbine hybrid system is known to be a promise alternative for power generation with high efficiency. This paper presents the third part of the parametric study of a Solid Oxide Fuel Cell/Gas Turbine (SOFC/GT) hybrid system generating 120 MW Net power. The studied parameters are Pressure $P$, pre-reformed fraction $X_r$, extraction fraction $f_s$, $H_2$ flow, and air flow. Their effects on the performances of SOFC-GT hybrid system are investigated. The Engineering Equations Solver (EES) simulation is established to analyze the SOFC-GT exergetic and energetic system performances. The results show that increasing the air and fuel flows enhance system exergy. In contrary, the pressure at the SOFC and the extraction fraction negatively affects the exergy performance of the hybrid plant. It is also found that the combustion chamber, pre-reformer, and SOFC represent the greatest exergy destroyers.

Keywords: gas turbine, SOFC, exergetic efficiency, parametric study

1. Introduction

Power generation with high efficiency and low emissions becomes a serious research topic. Fuel cells are considered as an appropriate technology. Among several fuel cells, Solid Oxide Fuel Cell (SOFC) is characterized by special advantages that make its coupling with different power cycles especially with Gas Turbine (GT) an attractive proposal to achieve high electrical and thermal efficiencies. Many papers studied SOFC/GT hybrid systems. This integration shows a high electrical efficiency [1]. Parametric, economic, energetic, and exergetic studies are established to optimize SOFC/GT systems [2, 3]. Also, the advancement in material technology and its application on SOFC [4], the use of different fuels, modeling techniques, various designs, techniques, and configurations have been proposed and studied [5–13]. Additional electrochemical systems, bottoming cycles, and chemical processes can be integrated in SOFC-Turbine hybrid system to enhance its efficiency such as the organic Rankine bottom cycle with cryogenic nitrogen assisting in CO$_2$ recovery used by Yang et al. [14]. A multi-generation system power investigated by Haghghi et al. gave 47.14% as an overall system exergy efficiency [15]. The solar array, the proton exchange membrane electrolyzer, and digester are added by Inac et al. to develop a highly renewable hybrid concept [16]. Gholamian et al. [17] found that ORC integrated with
thermoelectric generator is having high exergy efficiency in comparison of the basic ORC by 21.9%. Malico et al. [18] studied the integrated SOFC-absorption chiller system for cooling, heating, and power by utilizing waste heat from SOFC and found 68% thermal efficiency. Mehrpooya et al. [19] investigated SOFC-Ammonia water single effect absorption system with ORC combination and they found an efficiency of 62.4%.

Different architectures of hybrid systems are described in previous research. Coupling SOFCs thermally or chemically with bottoming power cycles and renewable energy conversion and storage devices achieves an important efficiency reaching 80% [20–23]. Valerie et al. [24] assessed a thermo-economic study of an indirect integration of a standard gas turbine cycle with an internal reforming SOFC system and bottoming Organic Rankine Cycle (ORC). They concluded that with toluene as working fluid an energy efficiency of about 4% and an exergy efficiency of about 62% are obtained. A supercritical CO$_2$ bottoming cycle was added by Meng et al. to operate the SOFC at higher power density with 70% system efficiency [25]. Many combinations show an important efficiency. Liu et al. found that 62.29% exergy efficiency was obtained using SOFC-GT-ORG-CO$_2$ CAPTURE [26]. An overall exergy efficiency of 47.14% was obtained by a multi-generation system for power, cooling, and hydrogen and water production [27]. An electrical efficiency of about 75.8% is obtained by Yi et al. [28]. An improvement of the exergy and the energy performances by 26.6 and 27.8% of SOFC-GT hybrid system compared to traditional gas turbine performances, respectively, is demonstrated by Haseli et al. [29]. A thermodynamic and exergo-economic analysis of a SOFC-GT cogeneration system were conducted by Mahmoudi and Khani [2]. They found that the economic and thermodynamic performances increase with the TIT and steam to carbon ratio. Harvey and Richter [30] used ASPEN plus simulator to study pressurized SOFC system, initially developed in Argonne National Laboratory. Later on in the 1997, Siemens Westinghouse delivered the first prototype for producing 220 kW via pressurized SOFC-GT. Santhanam et al. [6] studied an SOFC-GT system integrated to a bio-mass gasifier while integrating a heat pipe within the SOFC stack. They found reduction in exergy destruction and improvement in efficiency of the proposed system. The electric efficiency achieved for the proposed plant exceeds 72%. Ji et al. [10] compared performance assessment of integration of hybrid SOFC-GT cycle with different bottoming Rankine cycle alternatives. They concluded that triple combined cycle yields 3% higher efficiency as compared to dual combined cycle.

2. System description

The studied power plant is represented by Figure 1. It is mainly composed by a gas turbine cycle GT, a Solid Oxide Fuel Cell SOFC system, and an ammonia water absorption refrigerating system; also heat exchangers HE is used to recover and valorize the heat fluxes from the Gas Turbine and SOFC exhausts. Before feeding the SOFC, the fuel is pre-reformed for a specific portion. The required steam for pre-reforming is produced by the steam generator working with the exhaust heat 43 g from HE1. The outlet of the performing 3C will be completely reformed in the SOFC. After the compression through CA2 the ambient air 3a will be heated in HE1 to obtain 4C. Inside the SOFC, the chemical energy will be converted to electricity due to electrochemical reaction that occurs in the SOFC. Fuel cell exhaust 43a is compressed to 43c to be used to heat the air compressed by CA1 in the heat exchanger HE2. The fuel mixture (the gas 43d and the fresh fuel 2c) will feed the combustion chamber.
with the compressed heated air 1c. The exhaust flow from the combustion chamber 21a is expanded by the gas turbine GT to generate mechanical power which is converted in electrical generator to electricity. In addition, the flux 43f is used to activate the ammonia water absorption refrigerating system. The exhaust flux from the GT is transferred to the refrigerating system or to the stack.

3. Mathematical models

The purpose of exergy analysis is to determine the performance and identify the sources of irreversibility of the hybrid system.

3.1 SOFC

Characteristics of the fuel cell are selected according to ref. [31]. The SOFC is the seat of reforming, shifting, and electrochemical reactions. The used fuel composition is reported in Table 1. Developed SOFC model calculates voltages, power, and outlet flow parameters.

The power delivered by the SOFC is given by:

\[ P_{SOFC} = N_p \cdot E_{eel} \cdot I \]
The exergy balance and the exergetic efficiency of the SOFC can be expressed as:

$$\dot{E}_{3c} + \dot{E}_{4c} = \dot{E}_{43a} + \dot{w}_{\text{SOFC}} + \dot{E}_{\text{DSOF}}$$

$$\varepsilon_{\text{SOFC}} = \frac{\dot{w}_{\text{SOFC}}}{\dot{E}_{4c} + \dot{E}_{3c} - \dot{E}_{43a}}$$

### 3.2 Gas turbine

The gas turbine outlet temperature is given by

$$T_{5s} = T_{21a}/R^{(1-\frac{\gamma}{\gamma-1})};$$

Where R is the gas turbine expansion ratio

$$R = \frac{P_{21a}}{P_{5s}}$$

The power produced by the GT is calculated as follows:

$$W_{\text{TG}} = \eta_t \left( \dot{H}_{21a} - \dot{H}_{43e} + (1 - St) \left( \dot{H}_{43e} - \dot{H}_{5s} \right) \right)$$

The exergy balance and the exergetic efficiency of the GT can be expressed as:

$$\dot{E}_{21a} = \dot{E}_5 + \dot{w}_{\text{TG}} + \dot{E}_{\text{TG}}$$

$$\varepsilon_{\text{TG}} = \frac{\dot{w}_{\text{TG}}}{\dot{E}_{21a} - \dot{E}_5}$$

### 3.3 Combustion chamber

The exergy balance and the exergetic efficiency of the combustion chamber can be expressed as:

$$\dot{E}_{2c} + \dot{E}_{m} = \dot{E}_{21a} + \dot{E}_{\text{DC}}$$

$$\varepsilon_{\text{CC}} = \frac{\dot{E}_{21a}}{\dot{E}_{2c} + \dot{E}_{m}}$$
3.4 Heat Exchangers

Multiple gas-to-gas heat exchangers are proposed to recover heat. It is assumed that there is no heat transfer between these elements and the surrounding environment. The effectiveness-NTU method is used to determine the actual temperature changes for both cold and hot fluids, based on the heat exchanger type, effective heat transfer coefficient, and surface area. For a cross flow and unmixed fluid type heat exchanger, the effectiveness is expressed as [1]:

$$
\epsilon = 1 - \exp \left\{ \frac{\text{NTU}^{0.22}}{C_r} \left( \exp \left( -C_r \text{NTU}^{0.78} \right) - 1 \right) \right\}
$$

$$
C_r = \frac{C_{\text{min}}}{C_{\text{max}}}
$$

$$
C_{\text{min}} = \text{Minimum} \left( \dot{m}_c C_p_c, \dot{m}_f C_p_f \right)
$$

$$
\text{NTU} = \frac{UA}{C_{\text{min}}}
$$

The exergy balance and the exergetic efficiency of the heat exchangers are determined using the following equations:

$$
\dot{E}_{1b} + \dot{E}_{43c} = \dot{E}_{1c} + \dot{E}_{43d} + \dot{E}_{\text{ECTG}}
$$

$$
\epsilon_{\text{ECGT}} = \frac{\dot{E}_{1c} - \dot{E}_{1b}}{\dot{E}_{43c} - \dot{E}_{43d}}
$$

$$
\dot{E}_{3b} + \dot{E}_{43b} = \dot{E}_{3c} + \dot{E}_{43g} + \dot{E}_{\text{ECSOFC}}
$$

$$
\epsilon_{\text{ECSOFC}} = \frac{\dot{E}_{3c} - \dot{E}_{3b}}{\dot{E}_{43b} - \dot{E}_{43g}}
$$

3.5 Compressors

The outlet temperatures of used compressors are calculated using the following equations:

$$
T_{1b} = T_{1a} * R_1^{(1-\frac{1}{\gamma})}
$$

Where $R_1 = \frac{P_{1b}}{P_{1a}}$ is the compression ratio of comp$_{\text{GT}}$.

$$
T_{3b} = T_{3a} * R_3^{(1-\frac{1}{\gamma})}
$$

Where $R_3 = \frac{P_{3a}}{P_{3a}}$ is the compression ratio of comp$_{\text{SOFC}}$.

The power consumed by different compressors can be calculated using the following equations:

$$
\dot{W}_{\text{comp TG}} = \frac{(\dot{H}_{3a} - \dot{H}_{1b})}{\eta_c}
$$

$$
\dot{W}_{\text{comp TG}} = \frac{(\dot{H}_{43c} - \dot{H}_{43a})}{\eta_c}
$$

$$
\dot{W}_{\text{comp supp}} = \frac{(\dot{H}_{43a} - \dot{H}_{43a})}{\eta_c}
$$
The compressors’ exergy balance and the exergetic efficiency are determined using following equations:

\[ \dot{E}_{1a} + w_{\text{comp}\text{TG}} = \dot{E}_{1b} + E_{\text{D} \text{comp} \text{TG}} \]
\[ \varepsilon_{\text{comp} \text{TG}} = \frac{\dot{E}_{1a} - \dot{E}_{1b}}{w_{\text{comp} \text{TG}}} \]

\[ \dot{E}_{3a} + w_{\text{comp} \text{SOFC}} = \dot{E}_{3b} + E_{\text{D} \text{comp} \text{SOFC}} \]
\[ \varepsilon_{\text{comp} \text{TG}} = \frac{\dot{E}_{3a} - \dot{E}_{3b}}{w_{\text{comp} \text{SOFC}}} \]

\[ \dot{E}_{43a} + w_{\text{comp} \text{supp}} = \dot{E}_{43c} + E_{\text{D} \text{comp} \text{supp}} \]
\[ \varepsilon_{\text{comp} \text{supp}} = \frac{\dot{E}_{43a} - \dot{E}_{43c}}{w_{\text{comp} \text{supp}}} \]

### 3.6 Overall cycle efficiency

The net system power of hybrid system is given by

\[ P_{\text{NET}} = P_{\text{tot}} - W_{\text{comp} \text{TG}} - W_{\text{comp} \text{SOFC}} - W_{\text{comp} \text{supp}} \]

The energetic efficiency of gas turbine cycle is

\[ \eta_{\text{en,TG}} = \frac{W_{\text{TG}} - W_{\text{comp} \text{TG}}}{m_{\text{GT}} \cdot \text{PCI}} \]

The energetic efficiency of SOFC is

\[ \eta_{\text{en,SOFC}} = \frac{P_{\text{SOFC}} - W_{\text{comp} \text{SOFC}}}{m_{\text{SOFC}} \cdot \text{PCI}} \]

The energetic efficiency of the hybrid system is

\[ \eta_{\text{en,sys}} = \frac{P_{\text{NET}}}{(m_{\text{SOFC}} + m_{\text{GT}}) \cdot \text{PCI}} \]

### 4. Results and interpretations

1. **Effect of pressure**

   The air compressor consumes a lot of energy. The more the compression ratio increases, the more the energy requirement of this component increases. So, as the cell pressure increases, the compressor exergy decreases. Moreover, the pressure has a negative effect on the exergy efficiency of the fuel cell and the gas turbine as shown in Figures 2 and 3. Operating at a pressure equal to 200 kPa, the cell and the turbine exhibit exergy efficiencies of approximately 57.3 and 80.7%, respectively. Whereas for a pressure \( P = 1000 \text{ kPa} \), these efficiencies
become respectively 53.4 and 66.2%. In addition, the pressure variation has a small influence on the exergy efficiency of the heat exchanger of the gas turbine cycle and a large effect on the exergy efficiency of the heat exchanger of the SOFC cycle as shown in Figure 4.

2. Effect of the extraction fraction

The increase in the extraction fraction implies a decrease in the useful power. The turbine loses part of the load to be expanded by the extraction leading to a decrease in the power generated as illustrated in Figure 5. An extraction of 4.5% leads to an efficiency of 67.4%, while a 65.8% yield is obtained if the extraction is doubled. The effect of the extracted fraction on the exergy of the stack heat exchanger was also studied as shown in Figure 6. By increasing the extracted fraction, the exergy of the exchanger decreases. This decrease is due to the increase in energy flows due to the increase in fluid mass flow. The more the mass flow increases, the greater the irreversibility. For extracted fractions of 0.45 and 0.8, the exergy yields obtained are 82% and 79%, respectively. Furthermore, a practically negligible negative effect of the extracted fraction on
the fuel cell is observed, as shown in Figure 7. Indeed, by increasing from a 5% extraction fraction to 10%, the destruction of exergy increases by only 2%. However, this parameter has a positive effect on the pre-reformer. Figure 8
shows the variation of the exergy yield of the pre-reformer as a function of the extraction fraction. This yield increases with the indicated fraction. For an extraction fraction equal to 0.05, the pre-reformer has an exergy yield equal to 23.9% while for a fraction $f_s$ equal to 0.1, this yield reaches 25.3%.

3. Effect of $H_2$ flow

The variation in the flow of $H_2$ with constant oxidant flow represents in other words the variation of the fuel/oxygen ratio. This ratio affects the electrochemical reaction, temperature, and combustion reaction.

At a given air flow and precisely at a given oxygen flow, corresponds a maximum flow rate of $H_2$ which could be oxidized without heating the cell to a temperature that damages the materials constituting the cell.

Figures 9 and 10 illustrate the influence of $H_2$ flow rate on the exergy efficiency of the fuel cell and gas turbine, respectively. It can be seen that for the SOFC, the efficiency increases significantly with the $H_2$ flow, reaching a limit value of about 53.4% as shown in Figure 9. For a variation in the $H_2$ flow rate from 101.1 to 203.3 mol/s, the exergy efficiency of the cell increases by approximately 8%.
Likewise, the exergy efficiency of the gas turbine is improved with increasing $H_2$ flow rate. For the same range of $H_2$ flow rate variation, the exergy efficiency of the gas turbine increases by approximately 3.2% as shown in Figure 10.

A positive effect was observed for the pre-reformer as shown in Figure 11. For the same variation in flow, the exergy efficiency obtained respectively are 14.4 and 24.4%.

We therefore find that irreversibility can be reduced by increasing fuel flow. This is due to the increasing of the cell temperature which decreases cell polarizations and to the increasing of the temperature and inlet flow of the gas turbine. We also note that the more the $H_2$ flow rate increases, the more the fuel flow rate increases and then more chemical exergy is available to the reformer.
4. Effect of air flow

The SOFC intake air flow affects cell, heat exchanger, and turbine performances. Figure 12 shows the evolution of the SOFC exergetic efficiency as a function of the air flow. It is observed that the exergetic efficiency reaches a maximum value of approximately 53% for an optimum air flow rate equal to 362.2 mol/s. A higher air flow leads to a lower exergetic efficiency. This is explained by the fact that excess air cools the cell.

In addition, the more the molar air flow increases, the more the energy supplied to the cell increases, which leads to a higher exergy destruction.

In addition, the increase in the air flow leads to an improvement in the exergetic efficiency of the turbine as shown in Figure 13. For the same flow rate range, the gas turbine efficiency increases from 66.87 to 68.01% due to the increase in mass flow rate at the feed.
5. Exergetic efficiencies of principal components in optimal conditions

The exergetic efficiencies of the various components operating under optimal conditions are shown in Figure 14. It is noted that the combustion chamber, the pre-reformer, and the fuel cell have the lowest values of the exergetic efficiency. Indeed, the combustion chamber has the lowest exergetic efficiency. It virtually destroys 83.3% of the exergy that is received. The irreversibility of combustion is due to heat transfer, friction of fluids, mixing, and chemical reaction. It is difficult to assess the contribution of each process to the total rate of irreversibility. In reality, we can assimilate that the irreversibility due to friction and mixing is negligible compared to other irreversibilities. The destruction of exergy at the SOFC is also significant. Its exergetic efficiency is in the order of 53.56% under optimal conditions. It is attributed to thermodynamic and electrochemical irreversibilities. Besides thermal transfer, SOFC is the location of various chemical reactions. It should also be noted that the reformer is a source of significant degradation of exergy since it is fed by material flows at different temperatures and it is the location of chemical reactions. While the
destruction of exergy at the heat exchangers is explained by the difference in temperatures between the various circulating flows.

An exergetic analysis of the hybrid TG/SOFC system is developed. The exergy balances are established for the various components. The results obtained show that the exergy efficiencies are improved by increasing the pre-fixing fraction of the air and fuel flows. While the ambient temperature, humidity, fuel utilization factor, SOFC pressure, and the shrinkage fraction affect negatively the exergy performance of the hybrid plant. In addition, the exergy study made it possible to locate the inefficiencies of the system studied.

5. Conclusion

An exergy analysis of the hybrid TG/SOFC system is developed. The exergy balances are established for the different components. A parametric study made it possible to highlight the effects of the operating variables on the exergy efficiency of these components. The results obtained show that the exergy efficiencies are improved by increasing the pre-reforming fraction of the air and fuel flows. While the pressure at the SOFC and the extraction fraction negatively affect the exergy performance of the hybrid plant. In addition, the exergy study made it possible to locate the inefficiencies of the system studied. The combustion chamber, pre-reformer, and SOFC have proven to be the greatest exergy destroyers.

Acknowledgements

The author is extremely grateful to the head of Applied Thermodynamic Research Unit, National Engineering School of Gabes, Tunisia, Prof. Tahar Khir for his encouragement and technical support.

Author details

Salha Faleh¹,²* and Tahar Khir²

1 University of Hafr alBatin UHB, Saudi Arabia

2 Applied Thermodynamic Research Unit, National Engineering School of Gabes, Tunisia

*Address all correspondence to: sfaleh@uhb.edu.sa

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
References


novel multi-generation solid oxide fuel cell based system for production of electrical power, cooling, fresh water, and hydrogen. Energy Conversion and Management. 2019;197:111895


[29] Haseli Y, Dincer I, Naterer GF. Thermodynamic analysis of a combined...
gas turbine power system with a solid oxide fuel cell through exergy. Thermochim Acta. 2008;480:1-9
