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Comparison of Single-stage and Two-stage Tubular SOFC-GT Hybrid Cycles: Energy and Exergy Viewpoints

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P A P E R   I N F O

A B S T R A C T

In this work, single-stage and two-stage tubular solid oxide fuel cell /gas turbine (SOFC-TG) hybrid cycles are comparatively examined from the energy and exergy viewpoints. For this purpose, mass, energy and exergy balances are applied to all components of the cycles. The behavior of tubular solid oxide fuel cell modeled in this study is validated with the experimental test data of tubular SOFC developed by Siemens Westinghouse. The results of simulation show that two-stage SOFC-GT hybrid cycle not only generate more power, but also it has high efficiency in comparison to single-stage SOFC-GT. The values of first law efficiency and exergetic performance coefficient (EPC) are increased from 60.69% and 1.405 in single-stage SOFC-GT to 63.93% and 1.725 in two-stage SOFC-GT, respectively. This means that for equivalent generated power of single and two-stage SOFC-GT hybrid cycles, the amount of exergy destruction for two-stage SOFC-GT cycle is less than single-stage SOFC-GT. Also, exergy destruction of all components of the hybrid cycles is calculated separately and the results are compared. Finally, a parametric study is performed to find out optimal values for solid oxide fuel cell design parameters. Effects of these parameters are evaluated on efficiency, generated power and total exergy destruction of the hybrid cycles.

1. INTRODUCTION

It is expected that hydrogen fuel be one of the main sources of producing energy all over the world in future years. Fuel cell is an electrochemical device in which a high-quality electric energy will be produced due to the reaction of hydrogen and oxygen. Hence, fuel cell will be one of the sources of producing power and energy in the future [1]. Nowadays, solid oxide fuel cell is the main option in power plants, because in addition to the general advantages of fuel cells, its special advantages such as more efficient in comparison to other fuel cells, the possibility of reforming input fuel in the stack of fuel cell, no need to expensive catalysts and its low corrosion due to the use of solid electrolyte in its structure have increased the usage of this kind of fuel cell in comparison to other kinds of fuel cells. The idea

of combining different power cycles to optimize and lessen energy losses has been taken into consideration for a long time. Due to high operating temperature, solid oxide fuel cells pave the way for the exhaust gasses of the fuel cell to be used as a heat source for other cycles. One of these measures is the combination of solid oxide fuel cell (SOFC) with gas turbine cycle. The use of SOFC was introduced by Yoshida and Ide [2]. In the gas turbine cycle, combustion chamber contains the most amounts of losses. If we can prevent direct contact of air and fuel in the combustion chamber, we can reduce the total losses in the cycle remarkably and as a result more efficiency will be expected. Therefore, using the fuel cell in a gas turbine cycle can lead to both having a power plant with less pollution and also increasing its efficiency. Much research has been done in the field of SOFC and the SOFC-Gas Turbine combined cycle. Combining solid oxide fuel cell with a micro gas turbine by Siemens- Westinghouse Company

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was one of the first moves in this regard. Costamagna et al. [3] examined a hybrid system including a combined micro gas turbine and a high temperature fuel cell, and discussed the performance of fuel cell. Also, some other researches have been done by Park et al. [4], Calise et al. [5] and Rao and Samuelsen [6] in which most of them have dealt with numerical simulation of fuel cell. Chan et al. [7] presented a thorough analysis of overvoltage inside tabular solid oxide fuel cell stack and voltage sensitivity in relation to the fuel cell components thickness. Aloui and Halouani [8] examined voltage losses in SOFC and also the effect of carbon monoxide on the improvement of electrochemical performance. Palsson [9] investigated the combined cycle including a plate solid oxide fuel cell and a micro gas turbine. Jia et al. [10] investigated the effect of recycling exhaust gasses from the anode and cathode of SOFC and concluded that recycling exhaust gasses from cathode and anode leads to better efficiency and performance of the combined cycle. Akaya [11] presented an electrochemical model for solid oxide fuel cell in which the performance characteristics of a tabular solid oxide fuel cell are determined and fuel cell losses as well as the effect of various parameters on the cell performance are discussed thoroughly. Bavarsad [12] examined the solid oxide fuel cell and gas turbine hybrid cycle in which an external water source is used to reform input methane to hybrid cycle. Haseli et al. [13] analyzed the simple gas turbine cycle and solid oxide fuel cell with regard to mass analysis. Akaya et al. [14] analyzed the fuel cell/gas turbine/CHP system thermodynamically.

A comprehensive literature survey on different types of SOFC hybrid systems modeling is presented by Zabihian and Fung [15]. In this paper, key features of the fuel cell models are highlighted and model selection criteria are explained. Also, a detail example of SOFC-gas turbine cycle model, description of early models, models with different objectives such as parametric analysis, comparison of configurations, exergy analysis, optimization, non-stationary power generation applications, transient and off-design analysis, thermoeconomic analysis are studied.

Kouhi et al. [16] discussed economical fuel cell model including operational cost, startup cost and different tariffs on electricity during the day hours. Genetic algorithm is used to determine optimal operation of fuel cell power plant with six-minute change in load pattern. The results show that fuel cell power plant lead to $450.0245 annual saving in costs, and make the hybrid system cost-effective to implement in most places.

Duan et al. [17] investigated three different SOFC hybrid power systems with zero-CO_2 emission and their performances are analyzed and compared. Also, the effects of the main operating parameters on the overall performances of SOFC hybrid systems with CO_2

capture are investigated. The results show that the zero CO_2 emission SOFC hybrid systems still have higher efficiencies, which only decrease about 3-4% compared with that of the basic SOFC hybrid system without CO_2 capture. Choi et al. [18] simulated a triple combined cycle which combines a gas turbine combined cycle (GTCC) and a solid oxide fuel cell (SOFC) system. The impact of post-combustion carbon capture was also evaluated. In this work commercially available F-class and J-class gas turbines were considered. The analysis showed that the efficiency of the triple combined cycle is a weak function of the gas turbine class.

A hybrid solid oxide fuel cell and gas turbine power system model is developed by Chinda and Brault [19]. Two models have been developed based on simple thermodynamic expressions. A comparative study of the simulated configurations, based on an energy analysis is used to perform a parametric study of the overall hybrid system efficiency. Application of the simple fuel cell plants and with integrated gas turbine/steam turbine–fuel cell systems for power generation is reviewed by Choudhury et al. [20]. The analysis shows that the resulting maximum efficiency of this SOFC-combined system can be up to 90% depending upon the operating condition and configuration used. Thermodynamic and dynamic simulation capabilities of hybrid fuel cell gas turbine (FC/GT) combined cycles have been developed and demonstrated by Brouwer [21]. In this work such issues as Design considerations, Cycle configurations, hybrid FC/GT system performance, hybrid system dynamic operation potential and commercialization status have been examined.

In the present work, energy and exergy analyses are performed to the single-stage and two-stage tubular solid oxide fuel cell (SOFC)/gas turbine (GT) combined cycles. The objective of this paper is, in this regard, to study the entire combined cycles and their components throughout both energy and exergy assessments and compare these combined cycles. Also, the exergy destruction of all components of the combined cycles is determined through a comprehensive second law analysis. A parametric study is also performed to reveal the effects of various operating parameters of fuel cell on performance criteria of the combined cycles. The novelty of this study compared to previous ones is that in most previous works only single-stage SOFC is combined with gas turbines and the hybrid cycle is analyzed, but in this study both two-stage and single-stage tubular SOFC-GT hybrid cycles are analyzed and compared and the effect of combination multi-stage SOFC with gas turbine is investigated from energy and exergy viewpoint. Also, the exergy destruction rates of the components are calculated separately for both hybrid cycles and the effect of combination two-stage SOFC with GT has studied on the exergy destruction rates of the components of the cycles. To our knowledge, analysis of the SOFC-GT hybrid cycle from these

viewpoints has not been performed in the literature. Also, the parametric study carried out in this work is different form previous studies, and the effects of the changes of fuel cell stacks operating parameters are evaluated simultaneously.

2. SYSTEMS DEFINITION

Figures 1 and 2 show the schematics of the combined cycles. In Figure 1, which shows the single-stage SOFC and gas turbine combined cycle, at first, methane is compressed in the fuel compressor and its temperature and pressure increase; then, it is mixed with the exhaust gasses from the solid oxide fuel cell anode and due to reactions in the pre-reformer and internal reformer of SOFC stack, the fuel will be changed into hydrogen and enter the fuel cell anode electrode. Having passed the first and second heat exchanger, air whose temperature and pressure is increased in the air compressor, enters the fuel cell cathode and reacts with hydrogen. The exhaust gasses from the fuel cell anode contain a few percentage of hydrogen that is burned in the afterburner using the exhaust gasses from the fuel cell cathode. Having passed the first exchanger, the exhaust gasses from the Afterburner is expanded in the gas turbine and finally having passed the second heat exchanger, exit the cycle. In Figure 2 which shows the two-stage SOFC and gas turbine combined cycle, having passed the fuel

compressor, with regard to the ratio of the current density of the first and second fuel cell stack, methane is divided into two flows and after passing from the mixers and reformers of each stack, it enters to the anode of the fuel cell stack. After passing through the first and second heat exchanger, the input air of the combined cycle enters the cathode of the first stack and then the exit of the input air from the cathode of the first stack, whose temperature has also increased, enters to the second SOFC stack cathode. The anode exits of the first and second stacks will be combined and burned with the output air from the cathode of the second stack of the fuel cell in afterburner. Then having passed through the first heat exchanger, the exhaust gasses enter the gas turbine.

3. MODELLING

Steam reforming is needed to convert methane to hydrogen. For this reason, methane should be mixed with the exhaust gasses from anode containing a high portion of steam. Since steam reforming reaction is strongly endothermic, several problems such as carbon formation on the anode and thermal gradients at the entrance of fuel cell may be occurred in complete internal reforming in fuel cell stack. So in pre-reformer first a portion of methane is converted to hydrogen.
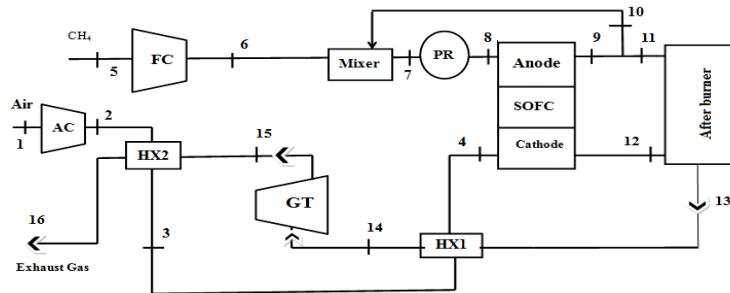

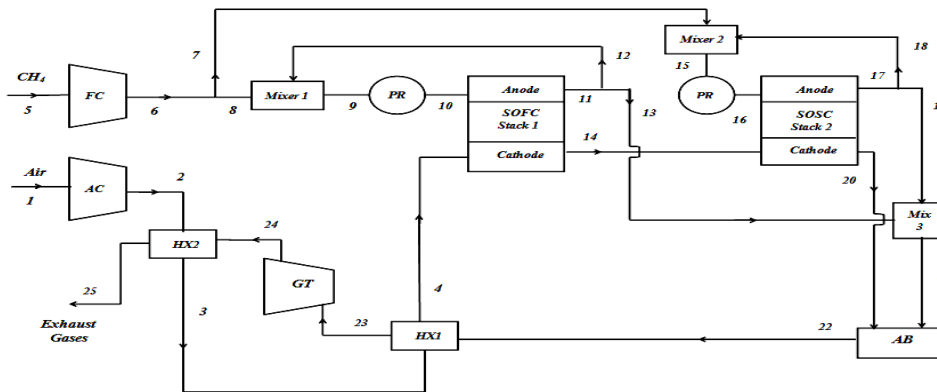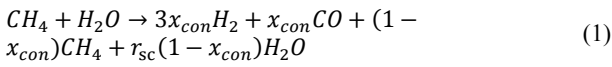**Figure 1.** Single-stage solid oxide fuel cell (SOFC) and gas turbine (GT) combined cycle configuration

Figure 2. Two-stage solid oxide fuel cell (SOFC) and gas turbine (GT) combined cycle configuration

TABLE 1. Constants of equilibrium of reforming and shifting reactions

	Reforming	Shifting
A	-2.63121×10-11	5.47301×10-12
B	1.24065×10-7	-2.57479×10-8
C	-2.25232×10-4	4.63742×10-5
D	1.95028×10-1	-3.91500×10-2
E	-6.61395×101	1.32097×101

The reforming reaction in pre-reformer is expressed as following [12]:

$$CH_4 + H_2O \rightarrow 3x_{con}H_2 + x_{con}CO + (1 - x_{con})CH_4 + r_{sc}(1 - x_{con})H_2O \tag{1}$$

$$x_{con} = \left(1 - \frac{\dot{n}_{8,CH_4}}{\dot{n}_{7,CH_4}}\right) \tag{2}$$

$$r_{sc} = \frac{\dot{n}_{10,H_2O}}{\dot{n}_{7,CH_4} + \dot{n}_{7,CO}} \tag{3}$$

where, X_{con} is the fraction of methane converted to hydrogen; rsc the steam to carbon ratio in molar basis, and ṅthe molar flow rate of a specific gas species. Then, remaining methane in reforming reaction in the cell is converted to H_2 and CO; and CO is converted to H_2 and CO_2 in shifting reaction [14]. The reforming and shifting reactions tacking place in the cell are:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{4}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{5}$$

where ṁ, ṅ and ż are considered as the consumed methane, carbon monoxide and hydrogen, respectively. Reforming and shifting reactions are considered to reach the thermodynamic equilibrium. So, equilibrium constant can be given as:

$$K_r = \left[\frac{(\dot{n}_{8,H_2} + 3\dot{x} + \dot{y} - \dot{z})^3 \cdot (\dot{n}_{8,CO} + \dot{x} - \dot{y})}{(\dot{n}_{8,CH_4} - \dot{x}) \cdot (\dot{n}_{8,H_2O} - \dot{x} - \dot{y} + \dot{z}) \cdot (\dot{n}_{8,tot} + 2\dot{x})}\right] P_{cell}^2 \tag{6}$$

$$K_s = \left[\frac{(\dot{n}_{8,H_2} + 3\dot{x} + \dot{y} - \dot{z}) \cdot (\dot{n}_{8,CO_2} + \dot{y})}{(\dot{n}_{8,CO} + \dot{x} - \dot{y}) \cdot (\dot{n}_{8,H_2O} - \dot{x} - \dot{y} + \dot{z})}\right] \tag{7}$$

whereẋ, ẏ and ż are calculated based on the reaction equilibrium. K_r and K_s are reforming and shifting equilibrium constants, respectively and are correlated to the temperature, as:

$$LogK = AT^4 + BT^3 + CT^2 + DT + E \tag{8}$$

The constants of this correlation are listed in Table 1 [10].The amount of hydrogen reacted at the electrochemical reaction (ż) is depending on fuel utilization factor:

$$\dot{z} = u_f(3\dot{x} + \dot{y} + \dot{n}_{8,H_2}) \tag{9}$$

On the other hand, the relation between current density of fuel cell and consumed mole of hydrogen is:

$$\dot{z} = \frac{i.A.N}{n_e.F} \tag{10}$$

where F is Faraday's constant and the value of n_e for electrochemical reaction of hydrogen is 2. N is the number of cell of each stack, $i$the current density of fuel cell and A the cell active area. The equation of Nernst potential (open circuit voltage) is given as [22]:

$$V_{Nernst} = -\frac{\Delta G_f^0}{n_eF} + \frac{RT_c}{n_eF}\ln\left(\frac{P_{H_2} \cdot \sqrt{P_{O_2}}}{P_{H_2O}}\right) \tag{11}$$

Some polarization losses must be taken when electrons flow through the circuit which decreases the cell voltage. These losses are classified into three groups as: a) Ohmic losses due to the electrical resistance of the electrodes and the resistance to the flow of ions through the electrolyte. The variation of these losses is linear with current density and computed as:

$$V_{ohm} = I \sum_k r_k \tag{12}$$

$$r_k = \sum_k \frac{\rho_k \cdot \delta_k}{A_k} \tag{13}$$

$$\rho_{k=a.exp(b/T_c)} \tag{14}$$

where r_k is the ohmic resistance, $\delta_k$the thickness and $\rho_k$the specific electric resistivity of cathode, anode and electrolyte. a and b are the constants that depend on the material, which are available in the literature for each fuel cell component[23].
b) Activation losses: This type of loss is related to the reaction mechanism occurring on the electrodes. This loss is calculated by the Butler-Volmer equation [11]:

$$i = i_0\left[exp\left(\frac{\beta n_e FV_{act}}{RT_c}\right) - exp\left(-\frac{(1-\beta)n_e FV_{act}}{RT_c}\right)\right] \tag{15}$$

where β is the charge transfer coefficient and is generally considered to be 0.5 [5]. i_0 is the exchange current density which is different for cathode and anode and calculated as [11] :

$$i_{0,a} = \gamma_a\left(\frac{P_{H_2}}{P_0}\right)\left(\frac{P_{H_2O}}{P_0}\right)\exp\left(-\frac{E_a}{RT_c}\right) \tag{16}$$

$$i_{0,c} = \gamma_c\left(\frac{P_{O_2}}{P_0}\right)^{0.25} exp\left(-\frac{E_c}{RT_c}\right) \tag{17}$$

where $\gamma_a$and γ_c are pre-exponential coefficients for anode and cathode, respectively. In addition, E is the activation energy which is different for anode and cathode.
c) Concentration losses: concentration losses are related to transmission of gasses through porous electrodes. This type of loss is calculated by Fick equation [24]:

$$V_{con} = V_{con.a} + V_{con,c} \qquad (18)$$

$$V_{con,a} = \frac{RT_c}{n_e F} \ln\left(\frac{1 - i/i_{L,H_2}}{1 + i/i_{L,H_2O}}\right) \qquad (19)$$

$$V_{con,c} = \frac{RT_c}{n_e F} \ln\left(\frac{1}{1 - i/i_{L,O_2}}\right) \qquad (20)$$

where i_L is the limiting current density and depends on cell temperature, chemical composition, component thickness, operating pressure, etc., and is calculated as:

$$i_{L,j} = \frac{n_e. F. D_{eff,j}}{R. T_c. L_k} p_j \qquad (21)$$

Here, D_{eff} is the effective gas diffusion factor that is employed to account for tortuous path of the molecules in the porous electrodes. All input parameters of the cell can be found in Tables 2 and 3. Overall overvoltage of fuel cell is determined as the sum of the mentioned losses. Hence, cell voltage can be expressed as:

$$V_{cell} = V_{Nernst} - V_{ohm} - V_{act} - V_{con} \qquad (22)$$

The produced power of fuel cell is calculated from:

$$\dot{W}_{SOFC} = V. i. A. N \qquad (23)$$

The net output power of combined cycle is calculated as:

$$\dot{W}_{net} = \dot{W}_{SOFC} + \dot{W}_{GT} - \dot{W}_{AC} - \dot{W}_{FC} \qquad (24)$$

And overall efficiency of combined cycle:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{n}_f. LHV} \qquad (25)$$

where LHV is the lower heating value of methane and $\dot{n}$ is the consumed mole of methane in combined cycle.
The exergy of each stream is considered as the sum of physical and chemical exergies [25]:

$$\dot{Ex}_{ph} = \sum_i \dot{m}_i \left((h_i - h_{0,i}) - T_0(s_i - s_{0,i})\right) \qquad (26)$$

$$\dot{Ex}_{ch} = \sum_i \dot{n}_i \sum_i \left(x_i ex_i^{ch} + RT_0 x_i \ln(x_i)\right) \qquad (27)$$

Here, ex_i^{ch} is the specific chemical exergy of the species of each stream and x_i is related to mole fraction of the species in the streams. Exergy destruction rate derived from the exergy balance can be given as:

$$\dot{Ex}_{D,i} = \sum_j \dot{Q}_j \left(1 - \frac{T_0}{T_j}\right) - \dot{W} + \sum_i (\dot{Ex}_i)_{in} - \sum_i (\dot{Ex}_i)_{out} \qquad (28)$$

And total exergy destruction of combined cycle can be expressed as:

$$\dot{Ex}_{D,tot} = \sum_i \dot{Ex}_{D,i} + \dot{Ex}_{exhaust} \qquad (29)$$

Exergetic Performance Coefficient (EPC) is defined as the ratio of net output power to total exergy destruction of combined cycle.

$$EPC = \frac{\dot{W}_{net}}{\dot{Ex}_{D,tot}} \qquad (30)$$

4. VALIDATION OF THE CELL SIMULATION

To examine the accuracy of the simulation, the obtained cell voltage-current density curve is compared with the experimental data of solid oxide fuel cell published by Siemens-Westinghouse [26]. According to Figure 3, it is clear that the results of the simulation are in good agreement with the experimental data and maximum error of the cell voltage is 4%.

5. RESULTS AND DISCUSSION

Operating parameters for simulation of combined cycles and the results are presented in Tables 4 and 5, respectively. As Table 5 shows, the net output power and efficiency for two-stage SOFC-GT combined cycle are 662.6 kW and 63.93%, respectively, while these values are 316.8 kW and 60.69% for single-stage SOFC-GT combined cycle. Also, it can be observed that EPC increases from 1.405 for single-stage SOFC-GT to 1.725 for two-stage SOFC-GT.

TABLE 2. Input parameters of SOFC

Component	$a(\Omega. m)$	$b(K)$	$\delta(m)$
cathode	0.0000811	600	0.0022
Anode	0.0000298	-1392	0.0001
electrolyte	0.0000294	10350	0.00004
interconnection	0.0012	4690	0.000085

TABLE 3. Input parameters of SOFC

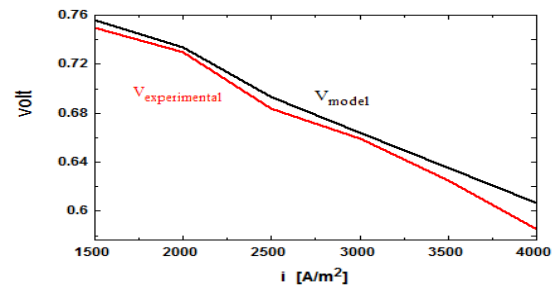|	
Anode activation energy (kJ/mol)	110
cathode activation energy (kJ/mol)	155
Anode pre-exponential factor (A/m^2)	7×10^9
cathode pre-exponential factor (A/m^2)	7×10^9

Figure 3. Comparison of simulation results with the experimental data published by Siemens-Westinghouse

TABLE 4. Model input data

Parameter	Value
Current density (A/m^2)	2800
Operating temperature of fuel cell (^{0}C)	1000
Fuel utilization factor of stacks	0.8
Air utilization factor	0.2
Pressure ratio	4
Active area of cells (m^2)	0.0834
Number of cells in each stack	1798
Carbon to steam ratio	2
Compressor isentropic efficiency (%)	80
Turbine isentropic efficiency (%)	85
Afterburner efficiency (%)	95
Heat exchangers effectiveness (%)	70
Pressure drop in fuel cell stack (%)	2
Pressure drop in heat exchangers (%)	2
Pressure drop in afterburner (%)	3
Lower heating value (LHV) of methane (J/mol)	808000

The equivalent net output power for two combined cycles, total exergy destruction of single-stage SOFC-GT is more than that of two-stage SOFC-GT. The exergy destruction of the components of the combined cycles is presented in Table 5. While only a small portion of input fuel to combined cycles reacts with outside air from the cathode of fuel cell in afterburner, but according to Table 6, exergy destruction of afterburner is approximately equal to exergy destruction of fuel cell stack. These results show that the fuel cell plays an important role in enhancing the performance of combined cycles.To better analyze the combined cycles thermodynamically, parametric study is done on the

single-stage and two-stage SOFC-GT combined cycles. Regarding Figure 4, if T_{C1} and T_{C2} are the operating temperature of the first and second fuel cell stack respectively, it can be seen that in the constant value of operating temperature of the second fuel cell stack, at first the net output power and efficiency of the two-stage SOFC-GT increase as the operating temperature of the first fuel cell increases, and then the trend is reversed. The reason for this is that at first, as the operating temperature of the first fuel cell stack increases, the voltage losses of the fuel cell decrease as well. As a result, the mentioned parameters are increased. As the operating temperature of the fuel cell increases more, Gibbs free energy will extremely decrease, and as a result Nernst voltage of the fuel cell, and consequently the net output power of the combined cycle are decreased. Thus, considering a constant value for the current density of the fuel cell, the amount of the input fuel does not change much and the efficiency is reduced. On the other hand, as previously mentioned, at first as the operating temperature of the first fuel cell stack increases, voltage losses of the fuel cell decreases, and as a result the exergy destruction of the fuel cell decreases to its minimum value. However, as the operating temperature increases more, Gibbs free energy decreases and the exergy destruction starts to increase. The same trend is repeated considering the constant value of operating temperature of the first fuel cell stack and increasing the operating temperature of the second fuel cell stack.

TABLE 5. Main results of the simulation

	Single-stage SOFC-GT combined cycle	Two-stage SOFC-GT combined cycle
First law efficiency (%)	60.69	63.93
Second law efficiency (%)	58.96	62.11
Net output power of combined cycle (kW)	316.8	662.6
Total exergy destruction of combined cycle (kW)	225.43	384.1
Exergetic performance coefficient	1.405	1.725

TABLE 6. The exergy destruction of the components of combined cycles

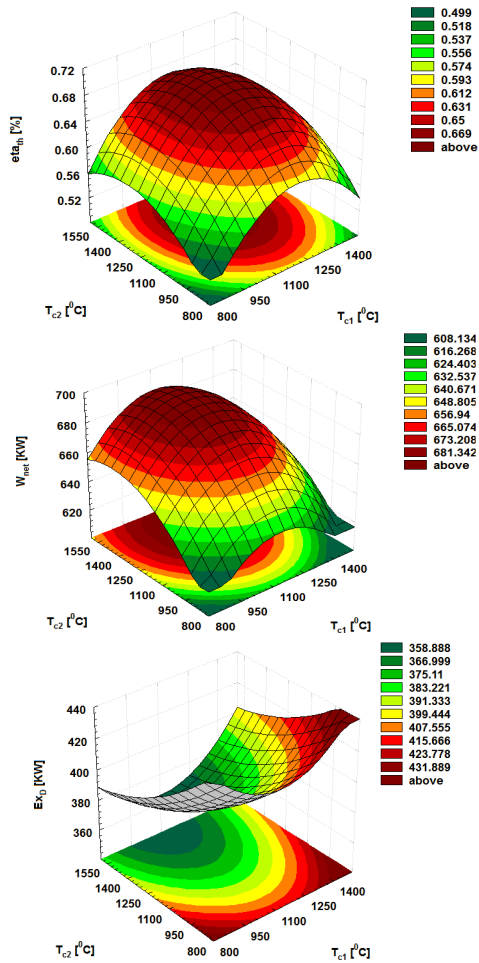| Components	Exergy destruction (kW)		Percentage of exergy destruction (%)	
	Single-stage SOFC-GT	Two-stage SOFC-GT	Single-stage SOFC-GT	Two-stage SOFC-GT
SOFC stack 1	31.08	33.45	13.78	8.7
SOFC stack 2	-----	32.56	-----	8.47
Air compressor	18.5	20.55	8.2	5.35
Fuel compressor	0.6203	1.232	0.275	0.32
Mixer 1	7.69	7.631	3.41	1.986
Mixer 2	-----	7.908	-----	2.059
Mixer 3	-----	0.009	-----	0.002
Pre-reformer 1	14.26	25.96	6.32	6.75
Pre-reformer 2	-----	26.61	-----	6.92
Afterburner	30.52	49.1	13.54	12.78
Heat exchanger 1	32.71	36.58	14.51	9.52
Heat exchanger 2	8.239	18.91	3.65	4.92
Gas turbine	19.79	19.16	8.78	4.99
Exergy destruction due to exhaust gasses from cycle	62.02	104.4	27.5	27.18
Total exergy destruction	225.43	384.1		

Figure 4. The variations of performance criteria of two-stage SOFC-GT with respect to first and second fuel cell stack operating temperatures
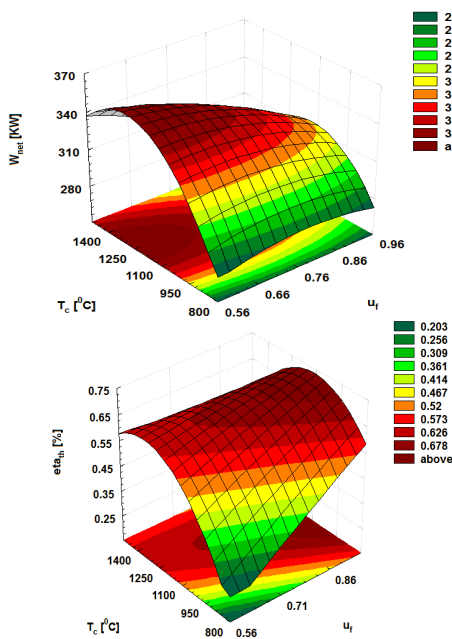

Figure 5. The variations of performance criteria of single-stage SOFC-GT with respect to fuel cell operating temperature and fuel utilization factor

Hence, it can be observed that the high value of first law efficiency of the two-stage SOFC-GT combined cycle occurs when the operating temperature of the first and second fuel cell stacks is 1180 and 1250 K, respectively; but, the highest value of net output power occurs in higher temperatures of the second fuel cell stack. Regarding Figure 5, it can be observed that in the constant value of operating temperature of the fuel cell stack in single-stage SOFC-GT, as fuel utilization factor of fuel cell increases, the partial pressure of hydrogen in the entrance of fuel cell anode decreases and as a result Nernst voltage of the fuel cell, decreases. This, decreases the net output power of the fuel cell stack, and as a result the net output power of the combined cycle decreases. On the other hand, as fuel utilization factor of the fuel cell increases, the amount of the input fuel to the combined cycle is decreased and as a result, the efficiency of the combined cycle will increase as fuel utilization factor increases, though the net output power of the combined cycle had decreased. Also, the more fuel utilization factor of fuel cell increases, the more the exergy destruction in the cycle will be. The change of EPC with the fuel utilization factor of fuel cell is similar to the first law efficiency.

According to Figure 6, if i_1 and i_2 are the current densities of the first and second fuel cell stacks, respectively, and considering a constant value for the current density of the second stack, increasing current density of the first stack increases the net output power of the two-stage SOFC-GT combined cycle. Figure 7 shows that in the constant value of current density of the solid oxide fuel cell, as the fuel utilization factor of the fuel cell increases, the first law efficiency of the combined cycle of the single-stage SOFC-GT is increased and the net power of the fuel cell and, in general, the net power of the single-stage SOFC-GT combined cycle is decreased. According to Figure 7, increasing the fuel utilization factor of the fuel cell decreases the voltage losses of the fuel cell and causes a decrease of the exergy destruction of the combined cycle. Increasing the current density causes the voltage losses to increase, and ultimately, it will lead to increase the exergy destruction.
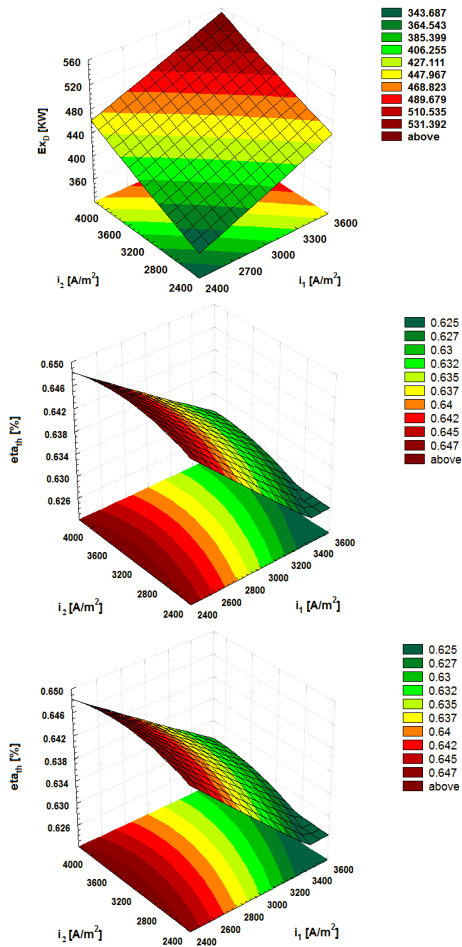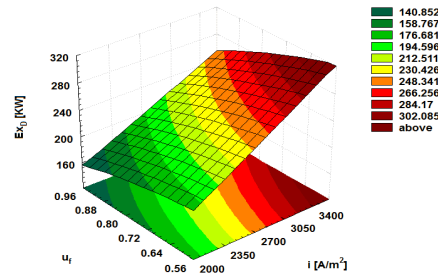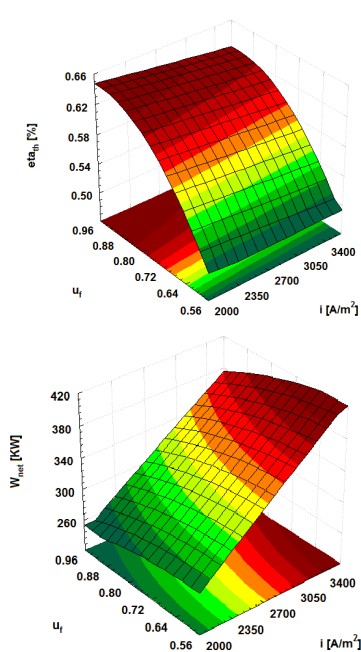
Figure 7. The variations of performance criteria of single-stage SOFC-GT with respect to fuel cell current density and fuel utilization factor

6. CONCLUSION

According to energy and exergy analysis results, it is observed that the two-stage SOFC-GT combined cycle not only generate more power, but also it has high efficiency in comparison with the single-stage SOFC-GT combined cycle. Also, EPC of the two-stage SOFC-GT is higher than that of the single-stage SOFC-GT. In addition, it is shown that the amount of exergy destruction of afterburner and fuel cell are almost equal, while a minute portion of input fuel to combined cycle is reacted in afterburner. Finally, a parametric study is done and the effects of the SOFC operating parameters are evaluated on the efficiency, net output power and total exergy destruction of combined cycles.

Figure 6. The variations of performance criteria of two-stage SOFC-GT with respect to first and second fuel cell stack current densities

7. REFERENCES

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Comparison of Single-stage and Two-stage Tubular SOFC-GT Hybrid Cycles: Energy and Exergy Viewpoints

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چکیده

در این تحقیق ترکیب یک مرحله‌ای و دومرحله‌ای پیل سوختی اکسید جامد لوله‌ای و توربین گازی با هم مقایسه شده‌اند. برای کلیه‌ی اجزای این دو سیکل ترکیبی قوانین پیوستگی، انرژی و اگزرژی نوشته شده و این سیکل‌های ترکیبی از نظرانرژی و اگزرژی شبیه‌سازی و با هم مقایسه شده است. نتایج بررسی سیکل‌های ترکیبی مورد مطالعه نشان می‌دهد که سیکل ترکیبی دو مرحله‌ای پیل سوختی اکسید جامد وتوربین گازی نسبت به سیکل ترکیبی یک مرحله‌ای پیل سوختی اکسید جامد وتوربین گازی هم دارای تولید توان بیشتر است، و هم بازده ترمودینامیکی آن به مقدار ۳ درصد بالاتر است. همچنین، میزان تخریب کلی اگزرژی سیکل ترکیبی دو مرحله‌ای پیل سوختی اکسید جامد وتوربین گازی به ازای تولید توان برابر برای سیکل‌های ترکیبی یک و دو مرحله‌ای، کمتر از سیکل ترکیبی یک مرحله‌ای پیل سوختی اکسید جامد وتوربین گازی، خواهد بود. به-علاوه،مطالعه پارامتریکی بر روی این سیکل‌های ترکیبی انجام شده‌و تاثیر پارامترهای طراحی پیل سوختی اکسید جامد لوله‌ای بر بازده ترمودینامیکی، توان تولیدی و اتلافات کلی این سیکل‌های ترکیبی تحلیل و بررسی است.

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