



## Modeling and Analysis of a Solid Oxide Fuel Cell Based Trigeration System with an Oxygenated Fuel by Using an Exergoeconomic Methodology for Power, Heating and Cooling Production

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### ABSTRACT

In the present study, thermo-economic analysis of a combined solid oxide fuel cell (SOFC) with a gas turbine, a generator-absorber heat exchanger (GAX) and heating process heat exchanger for heating, cooling and power production as a tri-generation system is conducted. Also, an external steam reformer is applied to convert methanol as oxygenated fuel to hydrogen for the electrochemical process of the SOFC. The influence of the primary design parameters (anode inlet temperature and current density) on several variables (energy and exergy efficiencies, exergy destruction, SUCP and unit costs of the products) are examined. Results showed that energy efficiency of proposed system was 55% higher than standalone SOFC. It was found that the maximum exergy destructions occurred in fuel and water mixer, after burner and SOFC. Unit cost of cooling was higher than the other products in the proposed system. It was equal to \$220.3/GJ at a specific condition, while unit cost of power and heating were \$34.22/GJ and \$1.24/GJ, respectively. That was because cooling system needed more components than other systems.

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### NOMENCLATURE

$\dot{C}$	cost rate, \$/h
$C$	cost per unit exergy, \$/GJ
$CEPEI$	Chemical Engineering Plant Cost Index
$CI_0$	cost index for the original year
$CRF$	capital recovery factor
$\bar{c}^{ch}$	standard chemical exergy, kJ/mol
$\dot{E}$	exergy rate, kW
GAX	generator absorber heat exchanger
$\dot{I}$	exergy destruction, kW
$i_r$	interest rate
$n$	life time of the system, year
$\dot{n}$	molar flow rate, mol/s
SOFC	solid oxide fuel cell
$U_f$	fuel utilization ratio
$W$	power, kW
$W_{FC,stack}$	output power of fuel cell, kW
$Z$	investment cost of component, \$
$\dot{Z}$	investment cost rate of component, \$/h
$\dot{Z}_{K,PY}$	cost at reference year, \$/h

### SUCP

Specific Unit Cost of Products

### Subscripts

AB	after burner
abs	absorber
AC	air compressor, AC current
AHE	air heat exchanger
Cond	condenser
des	desorber
EV	expansion valve
eva	evaporator
FC	fuel cell
fp	fuel pump
GAXA	GAX absorber
GAXD	GAX desorber
HR	heat recovery
INV	inverter
MIX	mixer

### Superscripts

CI	capital investment
OM	operation and maintenance

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## 1. INTRODUCTION

Energy crisis and global warming have been the most important issues in recent decades. Limited fossil resources and the world population growth rate make this crisis more important. Efficiency of conventional plants is less than 40%, but it can be enhanced using tri-generation systems up to 80%.

Fuel cells are an efficient approach for energy conversion. They can produce electricity directly from fuel and oxidant. Among different kinds of fuel cells, solid oxide fuel cell (SOFC) has more advantageous. It can use either internal or external reformer to produce hydrogen from fuels [1]. Currently, most fuel cells use natural gas which is mainly composed of methane. Methane and higher hydrocarbons are reformed to  $H_2$ ,  $CO$ ,  $CO_2$  and  $H_2O$  by reforming process and water-gas shift (WGS) reaction [2, 3]. Oxygenated chemical compounds contain oxygen as a part of their chemical structure. An oxygenated fuel, despite their significant lower energy density in comparison with hydrogen, is an alternative source of hydrogen. Methanol as an oxygenated fuel can be converted into hydrogen-containing mixtures by steam reforming [2].

SOFCs operate at high temperatures; consequently the high temperature waste heat is produced that has great

potential for tri-generation applications. A SOFC is commonly coupled with an organic Rankine cycle (ORC), gas turbine (GT) or a Stirling engine as a bottom cycle to improve the overall efficiency.

Massardo and Lubelli [4] investigated the feasibility of a SOFC with direct internal reforming of liquid fuels including methanol and ethanol. Al-Sulaiman et al. [5] proposed a tri-generation system consisting of a SOFC, an ORC, a heat exchanger and a single-effect absorption chiller and analyzed its performance from the viewpoint of the first law of thermodynamics. They found that the efficiency of the proposed plant was 22% higher than the stand-alone power plant. They also reported an exergy analysis for a proposed tri-generation system, and concluded that the exergy efficiency improved by 3–25% when the tri-generation plant was used instead of the stand-alone power cycle [6]. Chen et al. [7] proposed a thermodynamic model of direct ethanol fed internal reforming SOFC. They reported positive effect of reduction of cell voltage and increase of temperature on reforming of ethanol to hydrogen.

In the present study, energy, exergy and exergoeconomic analyses are performed on a novel tri-generation plant with a SOFC as prime mover.

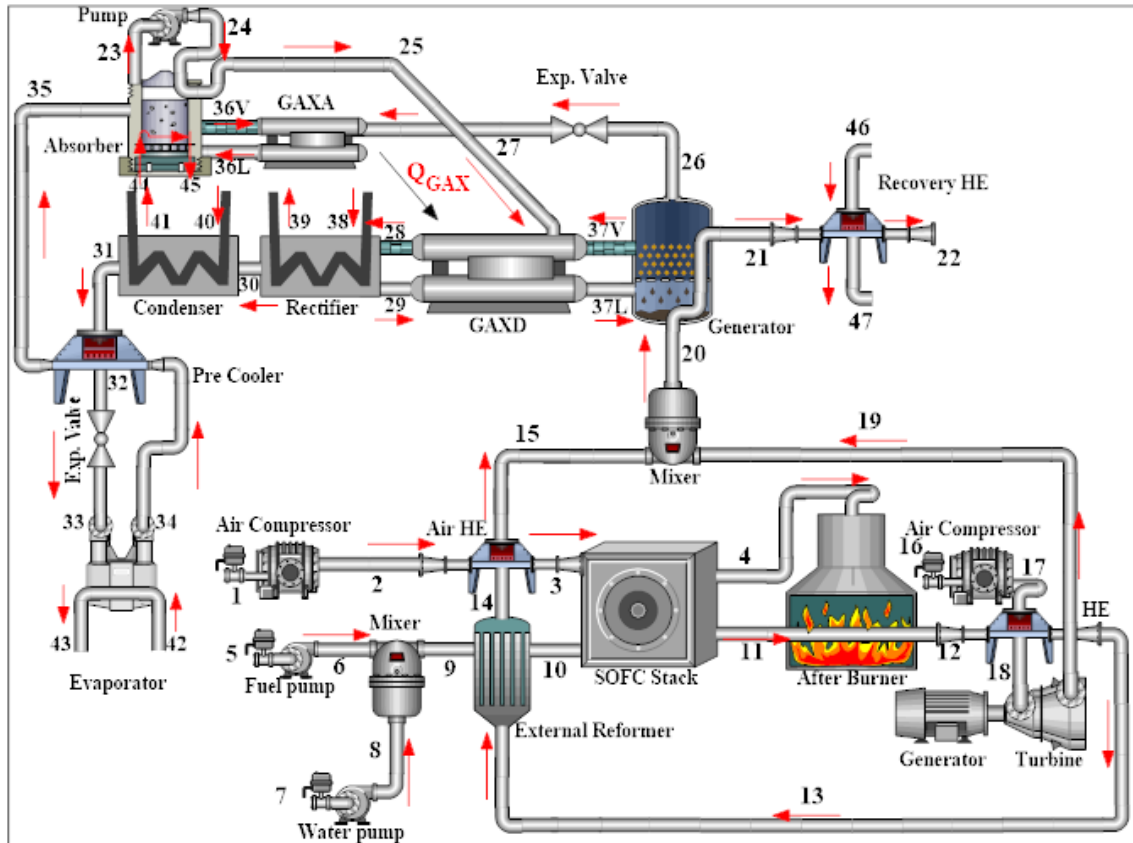


Figure 1. A schematic diagram of the proposed novel tri-generation system

The influences of the primary design parameters (anode inlet temperature and current density) on several variables (energy and exergy efficiencies, exergy destruction, SUCP, unit cost of the electrical power, unit cost of cooling, unit cost of heating and total unit cost of the products) are investigated.

## 2. SYSTEM DESCRIPTION AND ASSUMPTIONS

A schematic diagram of the proposed novel tri-generation system is shown in Figure 1. The oxygenated fuel (methanol), water and air are slightly pressurized to the operating pressure of the SOFC stack. Producing hydrogen from methanol needs reforming process and the steam reforming is the best choice. Mixture of water and methanol leaves mixer entering external steam reformer. The preheated air enters into cathode side while the products of the external reformer are supplied to the anode side. The electrochemical reactions occur in the fuel cell stack. An inverter is utilized to convert the DC power produced by the fuel cell into the AC power which is grid quality electricity. The excess air and unreacted fuel leave the SOFC and enter into the after burner (AB), combust completely and generate high-temperature gases. The exhaust gases from the AB warm up the working fluid of bottoming brayton cycle in a heat exchanger. In bottoming cycle, the hot and high pressure air expands through a turbine and produces power. In a mixer, the expanded gases are mixed with a part of exhaust gases from the air heat to the generator of the GAX system for cooling purposes. The remaining thermal energy is recovered through a HX for heating purposes. Details of the GAX cycle have been explained previously [8, 9].

The following assumptions are considered during the system modeling:

1. The system operates under steady state conditions.
2. Changes in the potential and kinetic energies are negligible.
3. All components operate adiabatically.
4. The atmospheric air is composed of 79% N<sub>2</sub> and 21% O<sub>2</sub>, on a volume basis.
5. All gases are treated as ideal gases.
6. The same temperatures exist at the anode and cathode outlets.
7. The fuel cell is insulated so there is no thermal interaction with the environment.
8. The refrigerant is saturated at the exits of the condenser and the evaporator.
9. Solutions at the exit of the absorber and generator are at the corresponding device temperatures.

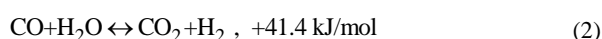
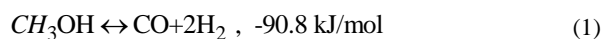
## 3. MODELING

In this section, the method for analyzing the proposed tri-generation system is presented, using the energy, exergy and exergoeconomic analyses. The engineering equation solver (EES) software is utilized to solve the resulting equations.

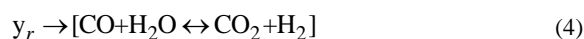
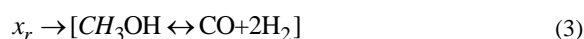
**3.1. Input Data** The input data for the analysis are listed in Table 1.

**3.2. External Reformer Modeling** The reactions occurring in the process of reformation of methanol are mainly endothermic and receive the necessary heat from the exhaust gases of the AB. The chemical reactions that occur in the external reformer are presented as Equations (1) and (2).

In Equation (1) methanol is converted into hydrogen. Equation (2) presents the water-gas shift reaction.



The mechanisms of chemical reactions at the external reformer are based on the following equations:



**TABLE 1.** Input data

Temperature difference between anode inlet and exit	100 K
DC-AC inverter efficiency	97%
Fuel compressor isentropic efficiency	85%
Air compressor isentropic efficiency	85%
Pump isentropic efficiency	85%
Fuel cell pressure drop	2%
Pressure drops in heat exchangers	2%
Efficiency of solution pump	50%
Degassing value of GAX system	0.3
Turbine pressure ratio	10
Pressure ratio of air and fuel compressors	1.2
Ambient temperature	298.15 K
Ambient pressure	101.3 kPa
Annual system operation hours	8000
Interest rate	12%
Life time of the system	20 years

By applying mass conversion rule, Equations (3) and (4), the molar flow rates of the flowing gases are determined as follows:

$$\dot{n}_{CH_3OH}[9] = x_r \quad (5)$$

$$\dot{n}_{H_2O}[9] = SCR \times \dot{n}_{CH_3OH}[9] \quad (6)$$

$$\dot{n}_{CO}[10] = x_r - y_r \quad (7)$$

$$\dot{n}_{CO_2}[10] = y_r \quad (8)$$

$$\dot{n}_{H_2}[10] = 2x_r + y_r \quad (9)$$

$$\dot{n}_{H_2O}[10] = \dot{n}_{H_2O}[9] - y_r \quad (10)$$

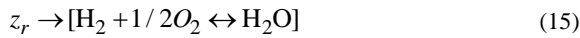
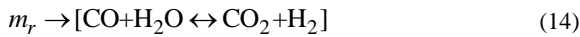
Due to the low reformation temperature of methanol, which is the characteristic of oxygenated fuels, there is no methanol in gases leaving the external reformer. Using equilibrium constant, molar flow rates and mole fractions are calculated:

$$\ln(K_s) = -\Delta\bar{g}_s^0 / \bar{R} \times T[10] \quad (11)$$

$$K_s = \frac{y_{CO_2}[10] \times y_{H_2}[10]}{y_{CO}[10] \times y_{H_2O}[10]} \quad (12)$$

$$\Delta\bar{g}_s^0 = \bar{g}_{s,CO_2}^0 + \bar{g}_{s,H_2}^0 - \bar{g}_{s,H_2O}^0 + \bar{g}_{s,CO}^0 \quad (13)$$

**3. 3. SOFC Modeling** The mechanisms of chemical and electrochemical reactions occurring at the anode and cathode of a fuel cell are based on the following equations:



The fuel utilization factor and the air utilization ratio are respectively defined as:

$$U_f = \frac{(Fuel)_{consumed}}{(Fuel)_{supplied}} = \frac{(H_2)_{consumed}}{(H_2)_{supplied}} = \frac{z_r}{\dot{n}_{H_2}[10] + m_r} \quad (16)$$

$$U_o = \frac{(Air)_{consumed}}{(Air)_{supplied}} = \frac{(O_2)_{consumed}}{(O_2)_{supplied}} = \frac{z_r / 2}{\dot{n}_{O_2}[3]} \quad (17)$$

By applying mass conversion rule, the molar flow rates of the flowing gases are determined as follows:

$$\dot{n}_{H_2O}[11] = \dot{n}_{H_2O}[10] + z_r - m_r \quad (18)$$

$$\dot{n}_{CO}[11] = \dot{n}_{CO}[10] - m_r \quad (19)$$

$$\dot{n}_{CO_2}[11] = \dot{n}_{CO_2}[10] + m_r \quad (20)$$

$$\dot{n}_{H_2}[11] = \dot{n}_{H_2}[10] + m_r - z_r \quad (21)$$

$$\dot{n}_{O_2}[4] = \dot{n}_{O_2}[3] - (z_r / 2) \quad (22)$$

$$\dot{n}_{N_2}[3] = 79 / 21 \dot{n}_{O_2}[3] \quad (23)$$

$$\dot{n}_{N_2}[4] = \dot{n}_{N_2}[3] \quad (24)$$

Using equilibrium constant, molar flow rates and mole fractions are calculated. The work rate produced by the SOFC stack can be expressed as follows:

$$I = j \times A_a \quad (25)$$

$$j = \frac{2FZ_r}{N_{FC}A_a} \quad (26)$$

$$\dot{W}_{FC,stack} = N_{FC} \times I \times V_c \quad (27)$$

where  $V_c$  is the cell voltage, defined as:

$$V_c = V_N - V_{loss} \quad (28)$$

**3. 3. 1. Validation of SOFC Model** Validation of the SOFC part of present work is done by experimental data of Ebrahimi et al. [10] with methane as fuel, and then the corresponding data is used with methanol. As it can be observed in Table 2, there is a good agreement between the proposed model and Tao et al. model. GAX cycle has been validated with the model proposed in the literature [11]. As different parts of a developed model are validated separately, it can be concluded that the present model is reliable and correct.

**3. 3. 2. Thermodynamic Analysis** Under steady state conditions and neglecting changes in the kinetic and potential energies, energy balance can be expressed for a component, as a control volume, as follows:

$$\dot{Q} - \dot{W} = \sum_i \dot{n}_i \bar{h}_i - \sum_e \dot{n}_e \bar{h}_e \quad (29)$$

The exergy rate balance of a control volume at steady state can be written as follows:

$$\dot{i} = \sum_j \left( 1 - \frac{T_0}{T_j} \right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{E}x_i - \sum_e \dot{E}x_e \quad (30)$$

**TABLE 2.** Comparison of results obtained from the model with the experimental values reported by Hong et al. [12]

Current density (A/m <sup>2</sup> )	Cell voltage (V) (Tao et al.)	Cell voltage (V) (model)	Error (%)	Power density (W/m <sup>2</sup> ) (Tao et al.)	Power density (W/m <sup>2</sup> ) (model)	Error (%)
2000	0.76	0.7677	+1	0.15	0.156	+4
3000	0.68	0.712	+4.7	0.21	0.216	+2.85
4000	0.62	0.646	+4.19	0.26	0.258	-0.769
5000	0.57	0.5648	-0.9	0.295	0.3	+1.6
6000	0.52	0.5304	+2	0.315	0.32	+1.5

Fuel: methane,  $U_f=0.85$ ,  $T_e=T_{stack}$

$\dot{I}$  is the rate of exergy destruction for a control volume. In Table 3, the expressions applied to determine the energy and exergy efficiency of the system, are presented. For comparing different energy systems, exergy and economic analyses are not adequate. A combination of these two analyses, called exergoeconomic analysis is a useful tool to identify and measure thermodynamic inefficiencies and their causes in an energy system.

Calculation of the costs of each product generated by the system as well as the optimization of the system is the objective of exergoeconomic analysis. For a system component receiving heat and producing power, the cost balance is written as follows:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \quad (31)$$

$$\dot{C} = c\dot{E} \quad (32)$$

where  $c$  is the cost value per exergy unit for each stream. The term  $\dot{Z}_k$  in Equation (33) is the total cost rate associated with the capital investment and operating and maintenance for the  $k_{th}$  component and can be calculated as [13]:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad (33)$$

$$\dot{Z}_k^{CI} = \left( \frac{CRF}{\tau} \right) Z_k \quad (34)$$

$$CRF = \frac{i_r(1-i_r)^n}{(1+i_r)^n - 1} \quad (35)$$

$$\dot{Z}_k^{OM} = \gamma_k Z_k + \omega_k \dot{E}_{p,k} + \dot{R}_k \quad (36)$$

where CRF is the capital recovery factor,  $n$  is the system life (20 years, except SOFC with 5 years) and  $\tau$  is the

**TABLE 3.** Energy and exergy expressions of system**Input energy rate**

$$\dot{Q}_{in} = \dot{m}_{CH_3OH} \times LHV$$

$$LHV = 20094 \text{ kJ / kg}$$

**Stack AC power of fuel cell:**

$$\dot{W}_{FC,stack,ac} = \eta_{inv} \times \dot{W}_{FC,stack}$$

$$\dot{W}_{net} = \dot{W}_{FC,stack,ac} + \dot{W}_T - (\dot{W}_{wp} + \dot{W}_{ac1} + \dot{W}_{ac2} + \dot{W}_{fc} + \dot{W}_{mainpump} + \dot{W}_{sfpump})$$

$$\eta_{FC} = (\dot{W}_{FC,stack,ac} - \dot{W}_{wp} - \dot{W}_{ac1} - \dot{W}_{fc}) / \dot{Q}_{in}$$

$$\eta_{el} = \dot{W}_{net} / \dot{Q}_{in}$$

$$\dot{Q}_h = \dot{m}_w (h_{71} - h_{70})$$

$$\dot{Q}_{eva} = \dot{m}_{eva} (h_{49} - h_{50})$$

$$\eta_{tri} = (\dot{W}_{net} + \dot{Q}_h + \dot{Q}_{eva}) / \dot{Q}_{in}$$

$$\dot{E}_{in} = \dot{m}_{CH_3OH} \times \bar{e}_{CH_3OH}^{ch}$$

$$\psi_e = \dot{W}_{net} / \dot{E}_{in}$$

$$\psi_{cog,c} = (\dot{W}_{net} + \dot{E}_{43}) / \dot{E}_{in}$$

$$\psi_{cog,h} = (\dot{W}_{net} + \dot{E}_{47}) / \dot{E}_{in}$$

$$\psi_{tri} = (\dot{W}_{net} + \dot{E}_{43} + \dot{E}_{47}) / \dot{E}_{in}$$

number of system operating hours. Also  $i_r$  is the interest rate (12%).  $\gamma_k$  is equal to 0.1 and the last two terms on the right hand side are negligible. Using the chemical engineering plant cost index (CEPCI), the cost of the system components is converted from the original year to a same reference year as follows:

$$\text{Cost at reference} = \text{original cost} \times \frac{\text{cost index for the reference year}}{\text{cost index for the original year}} \quad (37)$$

or,

$$\dot{Z}_{k,PY} = \dot{Z}_k \times \frac{CI_k}{CI_o} \quad (38)$$

#### 4. RESULTS AND DISCUSSION

The thermodynamic performance of the proposed tri-generation system and the effect of variations of design parameters are considered. Since current density and anode inlet temperature to the SOFC mainly affect system performance parameters, we focus on them here.

##### 4.1. Parametric Study

**4.1.1. The Effect of Current Density** The effect of current density variation on the system performance is shown in Figures 2 to 4. The energy efficiency of tri-generation system and exergy efficiencies of the considered system versus the current density are shown in Figure 2. Increased current density is the reason of reduction in the net electrical power and increase of molar flow rate of fuel and air. Therefore, an increase in current density leads to reduction of energy and exergy efficiencies. Increase of current density makes voltage loss increase and so, first law efficiency of tri-generation system laws. According to the definition  $\psi_e$  is the ratio of the net electrical power to the exergy carried to system by fuel. Higher current density needs more fuel and consequently more exergy is delivered to the system. On the other side, the net electrical power has a reducing behavior so  $\psi_e$  has a reducing trend. According to Table 3, and regarding the influence of the net electrical power and the inlet exergy carried by fuel on  $\psi_{(cog,c)}$  and  $\psi_{(cog,h)}$ , the decreasing trend of them is justifiable.

The influence of the current density on the irreversibility rates and SUCP is presented in Figure 3. It indicates that irreversibility rate of all components versus the current density, increases with increase of current density. The exergy destruction in the mixer, after burner and SOFC is considerably higher compared with other components of the system. The highest exergy destruction occurs in the mixer because of mixing of fuel and water.

The exergy destruction in the SOFC and after burner is due to the chemical reactions occurring in them and increases as the current density increases. By increasing the current density and consequently more fuel and air consumption and chemical reactions occurring in the SOFC, exergy destruction increases. In other components shown in Figure 6, the reason of increase in the exergy

destruction is increase in the amount of the available waste heat.

Regarding the definition of the SUCP, SUCP is the sum of unit cost of cooling, heating and power. When the current density increases, the SUCP decreases to a certain point and then increases and it has a minimum point. This is due to an increase in cooling capacity and follows the

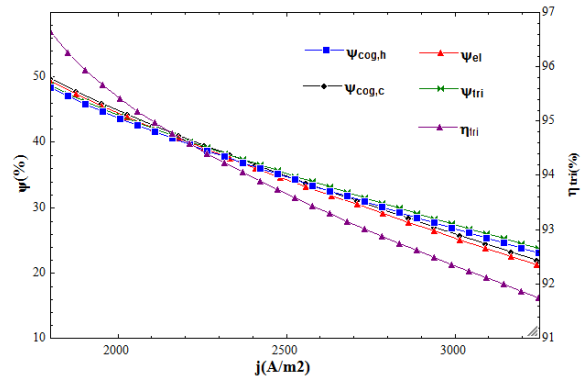


Figure 2. The influence of current density variation on exergy efficiency (T[10]=800, U<sub>f</sub>=0.85)

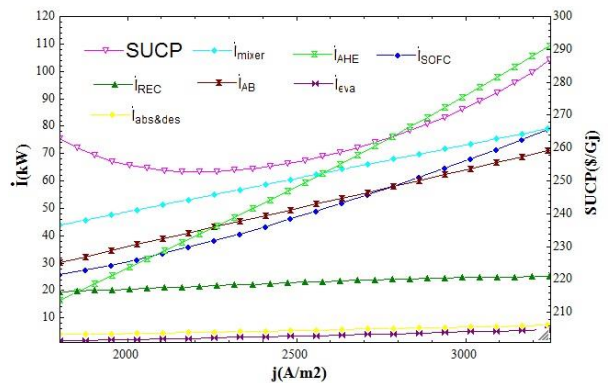


Figure 3. The influence of current density variation on exergy destruction in different components and SUCP (T[10]=800, U<sub>f</sub>=0.85)

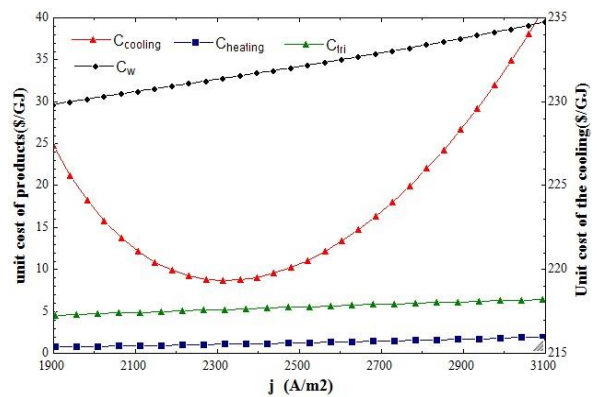


Figure 4. The influence of current density variation on unit costs of each product (T[10]=800, U<sub>f</sub>=0.85)

trend of  $C_{cooling}$  which is shown in Figure 4. It shows the influence of the current density on the unit costs of products. Referring to Figure 4, the unit cost of the net electrical power increases with an increase in the current density. This is mainly due to the reduction of the net electrical exergy efficiency and consequently the net electrical power produced. Additionally, the reduction of the net electrical exergy efficiency means more cost for fuel and larger heat exchangers for heating of more air. According to Figure 4, as the current density increases, the unit cost of the cooling decreases to a minimum point and then increases. There is an optimum point for unit cost of cooling which is found to be \$219.3/GJ at  $j=2317$  ( $A/m^2$ ). This trend is due to the fact that the increase in the current density resulted in an increase in both the cooling capacity and investment cost rate of the evaporator. Figure 4 depicts that the total unit cost of the products ( $C_{tri}$ ) increases with the increase of current density. As mentioned before, increasing current density leads to the reduction of the tri-generation exergy efficiency and that is the reason of this trend.

#### 4. 1. 2. The Effect of Anode Inlet Temperature

The effect of anode inlet temperature variation on the performance of the system is shown in Figures 5 to 7. The first law efficiency of tri-generation system and exergy efficiencies of the considered system versus the anode inlet temperature is shown in Figure 5. Increase of the net electrical power and decrease of the molar flow rate of air are due to increased anode inlet temperature. Therefore, as expected, while the anode inlet temperature increases, voltage loss decreases, hence first law efficiency of tri-generation system increases. For the same reason, the exergy efficiencies have an increasing behavior. Referring to the definition of  $\psi_e$ , as the ratio of the net electrical power to exergy carried to system by fuel, and considering that the increase of fuel flow rate is negligible during the increase of the anode inlet temperature,  $\psi_e$  rises. Despite the reducing trend of the cooling and heating capacities, the increase of the net electrical power dominates and as exergy intake through inlet fuel is almost constant, other exergy efficiencies improve with the increase of the anode inlet temperature. Figure 6 indicates that irreversibility rate of all components versus the anode inlet temperature in the range of 790 to 840 K, decrease with increasing of the anode inlet temperature except the mixing chamber and recuperator. The exergy destruction in the recuperator increases as anode inlet temperature rises. The reason is the increase of the hot flow temperature entering to the recuperator. This makes the temperature difference which is the reason of higher exergy destruction.

The exergy destruction in the mixer, after burner and SOFC is considerably higher compared to other components of the system. The mixer has the highest exergy destruction, and the mixing of fuel and water in

the mixer leads to exergy destruction which is almost constant and independent of the anode inlet temperature. Because the fuel and water flow rate and their inlet temperature are almost constant. The after burner and SOFC are in the second and third place of high exergy destruction. The exergy destruction in these two components is because of the chemical reaction occurring in them and decreases as the anode inlet temperature increases. At higher anode inlet temperatures, chemical reactions occur at higher temperature and are faster, with reduction of the voltage loss, the exergy destruction reduces.

The exergy destruction decrease rate in the air heat exchanger is faster compared with other components. The hot flow temperature at the inlet of air heat exchanger reduces with the increase of the anode inlet temperature and this means lower temperature difference in the heat exchanger, which is the reason of lowering the exergy destruction.

It can be seen in Figure 6 that, as the anode inlet temperature increases, the SUCP decreases to a point and then rises. There exists an optimal anode inlet temperature at which the minimum SUCP is attained and, here, the minimum SUCP is \$245.3/GJ at 826 K. As mentioned before, the behavior of SUCP is a function of the unit cost of cooling, heating and power, its behavior is a sum of these factors behavior.

Figure 7 shows the influence of anode inlet temperature on the unit costs of the products. In Figure 7, an increase in the anode inlet temperature is observed to lower the unit cost of net electrical power which is due to higher net electrical power in almost fixed fuel flow rate and less air molar flow rate. The cost of heating reduces too because of higher temperature of hot flow. But the unit cost of cooling has a different trend. At first, with an increase in anode inlet temperature, it decreases to a minimum point equal to \$214.5/GJ at 826 K, and then increases up to \$218.3/GJ. It can be observed that an increase in the anode inlet temperature leads to a decrease in the unit cost of all products due to the reduction of unit cost of heating and net electrical power.

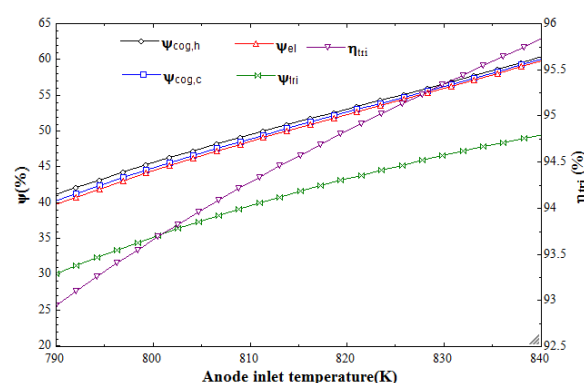
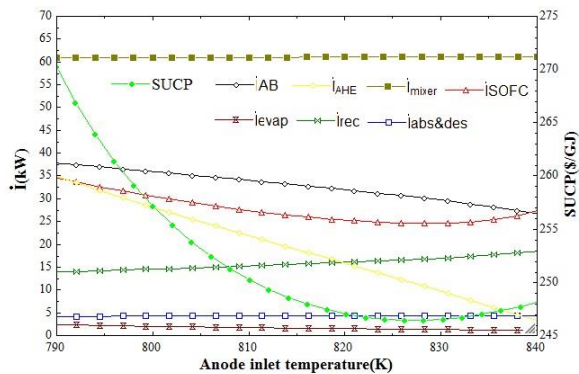
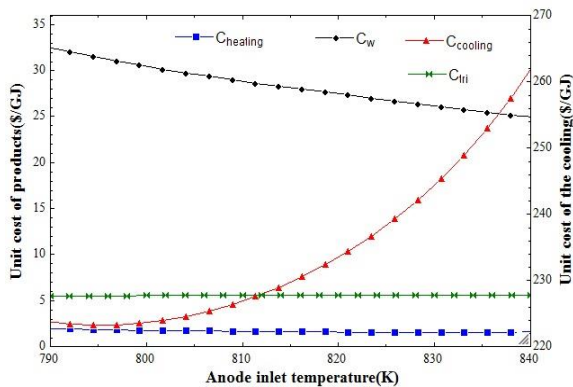


Figure 5. The influence of anode inlet temperature variation on exergy efficiency ( $j=2500$ ,  $U_T=0.85$ )





**Figure 6.** The influence of anode inlet temperature variation on exergy destruction in different components and SUCP ( $j=2500$ ,  $U_f=0.85$ )



**Figure 7.** The influence of anode inlet temperature variation on unit costs of each product ( $j=2500$ ,  $U_f=0.85$ )

## 5. CONCLUSIONS

A novel tri-generation system based on a SOFC with an external reformer and methanol as oxygenated fuel is proposed and analyzed. The exergy and exergoeconomic balances are performed. The influences of two design parameters (current density and anode inlet temperature) on the performance of the system are assessed. The following main conclusions are drawn from this research:

- Energy efficiency of proposed system is 55% higher than stand-alone SOFC.
- An increase in current density results in a decrease in energy and exergy efficiencies.
- Exergy destruction decreases by an increase in anode inlet temperature but it increases while current density is increased.
- It is observed that an increase in anode inlet temperature, has a meaningful effect on energy and exergy efficiency and increases them.
- Unit cost of heating and the unit cost of net electrical power increase by an increase in current density.

- In both cases, SUCP and unit cost of cooling lowers to a minimum point and then increase. SUCP has a minimum point equal to \$245.3/GJ at 826 K, and the minimum value of \$252.8/GJ at the current density of 2214 A/m<sup>2</sup>.
- Increasing of anode inlet temperature decreases the unit cost of net electrical power and the cost of heating. Unit cost of cooling has different trend, it lowers to a minimum point and then increases.
- Maximum exergy destruction occurs in fuel and water mixer. After burner and SOFC are in second and third place, respectively.
- Unit cost of cooling product is higher than the other products in the proposed system. It is equal to \$220.3/GJ at a specific condition, while unit cost of power and heating are \$34.22/GJ and \$1.24/GJ, respectively.

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## Modeling and Analysis of a Solid Oxide Fuel Cell Based Trigeration System with an Oxygenated Fuel by Using an Exergoeconomic Methodology for Power, Heating and Cooling Production

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در این تحقیق، یک سیستم تولید سه گانه بر اساس استفاده از یک پیل سوختی اکسید جامد با سوخت متانول ورودی به ریفورمر خارجی، سیستم تبرید گس و بازیاب حرارتی از دیدگاه ترمودینامیکی و اگزورژواکونومیکی مورد بررسی قرار گرفته است. در سیستم پیشنهادی از یک ریفورمر خارجی برای تبدیل سوخت متانول به هیدروژن، جهت مصرف در واکنش های الکتروشیمیایی پیل سوختی استفاده شده است. هدف از این تحقیق بررسی تأثیر پارامترهای اساسی (دمای جریان ورودی به آند و چگالی جریان) بر روی چندین متغیر (بازده انرژی و اگزورژی، تخریب اگزورژی و هزینه واحد توان تولیدی) بوده است. نتایج این بررسی نشان می دهند که بازده انرژی سیستم پیشنهادی از بازده پیل سوختی به تنهایی بیش از ۰.۵۵٪ بیشتر است. همچنین مطالعه نشان می دهد که بالاترین نرخ تخریب اگزورژی در محفظه اختلاط، پس سوزو پیل سوختی رخ می دهد. از طرفی با استناد به نتایج بدست آمده، هزینه واحد سرمایه گذاری تولیدی نسبت به سایر محصولات بالاتر است. در شرایط معین ذکر شده در این تحقیق، هزینه واحد سرمایه گذاری تولیدی و هزینه واحد توان تولیدی به ترتیب برابر با  $220.3/GJ$  و  $34.22/GJ$  بوده و هزینه واحد توان حرارتی برابر با  $1.24/GJ$  می باشد. علت بالا بودن هزینه تولید توان سرمایه گذاری، تجهیزات لازم برای تولید آن است.

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