Effect of Operating Temperatures on the Performance of a SOFC/GT Hybrid System

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ABSTRACT

This article presents a steady-state thermodynamic model of a solid oxide fuel cell/gas turbine hybrid cycle which developed by using a simulation software, MATLAB®. The hybrid model integrates a zero-dimensional level SOFC model with gas turbine. The hybrid system was used to study the effects of some operation parameter such as SOFC operating temperature, and current density on the specific work output, electrical efficiency, and exergy efficiency of a generic hybrid cycle. The results show that if the SOFC operating temperature, the power output, electrical efficiency, and exergy efficiency increase. The electrical efficiency of the hybrid system increase from 62% to 68%, and the exergy efficiency of the hybrid system increases from 60% to 66% when the operation temperature increases from 600°C to 750°C at a current density of 6000 A/cm2. On the other hand, the system efficiency and exergy decreases with an increase in the current density.

KEYWORDS: *Hybrid system, SOFC operating temperature, Exergy , Efficiency*

Introduction

Solid oxide fuel cell is a favorable technology for electricity generation and it has great potential for a diverse range of combined heat power applications because it operates at elevated temperature (600–1000 °C) amidst fuel cells , and very high electrical efficiencies can be achieved [1]. The SOFC can be applied with a difference of power generation systems; both stationary power generators and auxiliary power sources [2, 3]. Combining a SOFC with common heat engines like gas turbines can be increases the efficiency to reaches 70% [4] . Therefore, integrated of SOFC-GT systems have attracted the notice of many investigator because of the boost in efficiency, capability of heat recycling, and created electrical power in diverse capacities [5] [6][7][8]. Bavarsad et al. [9] studied the integrated of SOFC-GT hybrid cycle established on the first and second law of thermodynamics. They investigated the effect of some operation parameters such as the operating temperature, air flow ratio, fuel flow ratio, and operating pressure. Rajabinasab et al [10] investigated the influence of recycling SOFC products on the power output and electrical efficiency of integrated (SOFC-GT) hybrid system. Oryshchyn et al [11] designed a hybrid systems of SOFC-GT for different levels of SOFC fuel utilization. They showed that the Lower fuel utilization factor increased the Nernst potential, and GT inlet temperature. Yi et al [12] presented different applicable options for combining a GT/SOFC to ensure very high power generation electrical efficiency.

This study introduces a SOFC stack model based on the methane feed planar internal reforming SOFC technology and integrated with gas turbine in a hybrid system. Different operation temperature were applied to understand its effect on the power produced, efficiency, and exergy of the hybrid system.

SYSTEM MODELING AND ASSUMPTIONS

Solid oxide fuel cell hybrid systems consist of a stack , and auxiliary components, whose arrangement strongly depends on the particular application. For the purpose of this study, the system (Figure 1) consists of a SOFC stack, a combustion chamber, a gas turbine, a water pump, mixers, compressors and heat exchangers. The developed model for SOFC is made on the following assumptions, and the input parameters to the hybrid system are listed in Table 1:

- Steady state conditions.
- Air, methane and water enter the fuel cell with the same temperature.
- The reforming reaction is completely developed in the SOFC
- The stream temperatures at the exits of the SOFC cathode and the anode are the same.
- There is no heat interaction with the environment.
- The pressure drop within the cell stack is neglected,
- Only hydrogen is electrochemically reacted. CO is converted to CO2 and H2 by water–gas shift reaction.

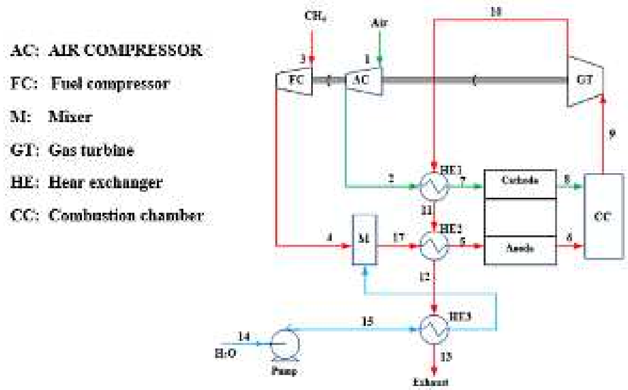

Figure1. Schematic Diagram of SOFC /GT hybrid system

Table1. The SOFC stack parameters

Parameter	Value
Specific resistivity of anode	$95 \times 10^6 \exp(-1150/T_{sofc})^{-1}$
Specific resistivity of cathode	$42 \times 10^6 \exp(-1200/T_{sofc})^{-1}$
Specific resistivity of electrolyte	$3.34 \times 10^4 \exp(-10300/T_{sofc})^{-1}$
Specific resistivity of interconnection	$9.3 \times 10^6 \exp(-1100/T_{sofc})^{-1}$
Active surface area	$0.01\ (m^2)$
Thickness of anode	$0.05 * 10^{-4} (m)$
Thickness of cathode	$0.005 * 10^{-4} (m)$
Thickness of electrolyte	$0.001 * 10^{-4} (m)$
Thickness of interconnect	$0.3 * 10^{-4} (m)$
Exchange current density of anode	$6500 (A/m^2)$
Exchange current density of cathode	$2500\ (A/m^2)$
Baseline current density	$6000\ (A/m^2)$
Effective gaseous diffusivity through anode	$0.2 * 10^{-4} (m^2/s)$
Effective gaseous diffusivity through cathode	$0.05 * 10^{-4} (m^2/s)$
Stack pressure drop	$2\ \%$
Fuel utilization factor	$0.85(-)$
Number of cell	667

FUEL CELL MODEL

The fuel cell used in this research is a type of planar SOFC with internal reforming. Reforming processes is required to convert the fuel into hydrogen (H_2) in a solid oxide fuel cell fed by a conventional fuel like methane (CH_4). The techniques of the reforming and electrochemical reactions that occur at the electrodes are based on the following equilibrium equations:

Steam reforming

$$x \rightarrow \quad CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{1}$$

Water gas Shifting

$$y \rightarrow \quad CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2}$$

Electrochemical reaction

$$z \rightarrow \quad H_2 + \tfrac{1}{2}O_2 \leftrightarrow H_2O \tag{3}$$

where x, y, and z are the molar rates of CH_4 converted in reforming reaction, carbon monoxide converted in shifting reaction, and hydrogen converted in the electrochemical reaction, respectively.

The reversible voltage of each planar SOFC is calculated by the Nernst equation:

$$E_{Nernst} - E^{\circ}(T,P) + \frac{RT}{n_e F}\left[\frac{p_{H_2} \cdot p_{O_2}^{1/2}}{p_{H_2O}}\right] \tag{4}$$

where E° is the fuel cell voltage at standard conditions; R is the universal gas constant; T is the SOFC operating temperature; n_e is the number of moles of electrons transferred per mole of fuel consumed.

The cell voltage E_{cell}, is calculated according to equation (5):

$$E_{cell} = E_{Nernst} - \eta_{act} - \eta_{ohm} - \eta_{con} \tag{5}$$

The activation losses η_{act} is obtained by simplifying the Butlere-Volmers equation of the sum of activation losses of the anode and cathode:

$$\eta_{act} = \frac{RT_{sofc}}{F}\sinh^{-1}\left(\frac{i}{2i_{oa}}\right) + \frac{RT_{sofc}}{F}\sinh^{-1}\left(\frac{i}{2i_{oc}}\right) \tag{6}$$

The ohmic losses are referred to the transmit of ions and electrons in the electrolyte, electrodes, and internal connectors. The ohmic losses are calculated by the following equations (7-8):

$$\eta_{ohm} = \eta_{ohm,an} + \eta_{ohm,ca} + \eta_{ohm,el} + \eta_{ohm,int} \tag{7}$$

$$\eta_{ohm} = i(\rho_{an}\delta_{an} + \rho_{ca}\delta_{ca} + \rho_{el}\delta_{el} + \rho_{int}\delta_{int}) \tag{8}$$

The concentration losses is calculated by the following equation:

$$\eta_{con,\ a/c} = -\frac{RT_{sofc}}{n_e F}\ln\left(1 - \frac{i}{i_{L,a/c}}\right) \tag{9}$$

where, $i_{L,a/c}$ is the limiting current density.

The power produced by SOFC stack can be obtained based on the cell voltage by equations (10-11):

$$v_{stack} = E_{cell} \cdot n_{cell} \tag{10}$$

$$\dot{W}_{SOFC} = i.A_{cell} \cdot E_{cell} \cdot n_{cell} = i.A_{cell} * v_{stack} \tag{11}$$

GAS TURBINE MODEL

By calculating the turbine inlet temperature from the energy balance of the combustion chamber, and knowing compression ratio, and the isentropic efficiency of the gas turbine , the exhaust gas temperature and the actual power of the gas turbine can be obtained as:

$$\frac{T_{in}}{T_{out}} = \left(\frac{p_{in}}{p_{out}}\right)^{\frac{k-1}{k}} \tag{12}$$

$$\dot{W}_{GT} = \dot{m}_i \cdot C_{p,i} \cdot \eta_{GT}\ [T_{in} - T_{out}] \tag{13}$$

SYSTEM PERFORMANCE

The net output power , the electrical efficiency, and the exergy efficiency are obtained by the following equations:

$$\dot{W}_{net} = \sum \dot{W}_{generate} + \sum \dot{W}_{consume} \quad (14)$$

$$\eta_{ele} = \frac{\dot{W}_{net}}{\dot{n}_f LHV_f} \quad (15)$$

$$\psi_{ele} = \frac{\dot{W}_{net}}{\dot{n}_f \bar{e}_f^{kim}} \quad (16)$$

Where $\dot{n}_f$ is the molar flow rate of fuel, LHV_f is the lower heating value of fuel, and $\dot{n}_f\ \bar{e}_i^{kim}$ is the standard chemical exergy of gases.

Results and discussion

The impact of the different SOFC operating temperatures on the thermodynamic performance of the hybrid system such as power output, electrical efficiency and exergy efficiency is discussed. Figures 2-3 present the influence of current density on the SOFC voltage and power density with different operating temperature. It is seen from these figures that an increase in current density causes a reduction in cell voltage which is proportional to SOFC power density. It is observed in Figure 3 that the power density of SOFC stack enhances at high SOFC operating temperature . The power density for SOFC stack ranges approximately from 16 kW to 39 kW for the range of current density shown for a SOFC operating temperature of 750 °C.

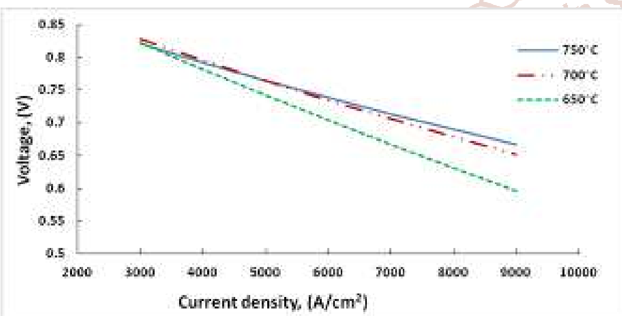

Figure2. Polarization curve for three different temperatures

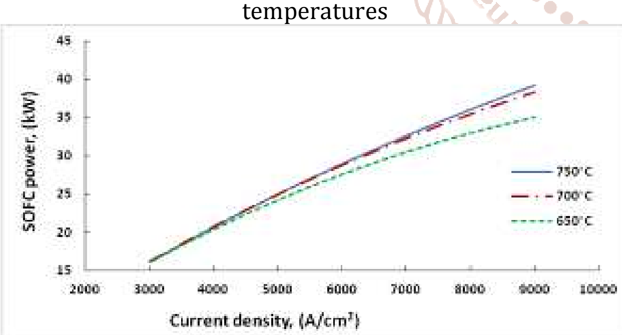

Figure3. SOFC power as a function of current density for three different temperatures

Figures 4-7 show the influence of current density on the power output, gas turbine power output, electrical efficiency, and exergy efficiency with different SOFC operating temperature, for a fuel utilization factor of 0.85, and a system pressure of 8 bar.

The effect of current density on the hybrid system power output indicates in Figure 5. It is observed from this figure that the power output from the hybrid system increases with an increase of current density, and SOFC operating temperature. The power output from the hybrid system ranges approximately from 18.2 kW to 45.7 kW for the range of current density shown, and a SOFC operating temperature of 750 °C. It is seen also from the results when the operation temperature increases from 600°C to 750°C at current density of 6000 A/cm², the power output from the hybrid system increases from 30.4 kW to 33,28 kW.

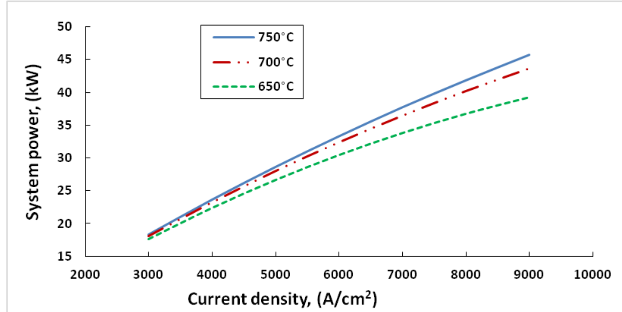

Figure4. Net system power as a function of current density for three different temperatures

Figure 5 indicates the effect of current density on the gas turbine power output, and the network of the gas turbine for several operating temperature. The figure showed that the GT power output increases with increasing of current density and SOFC operating temperature but the most power output from the gas turbine (approximate 75%) is used to drive the compressors and pump.

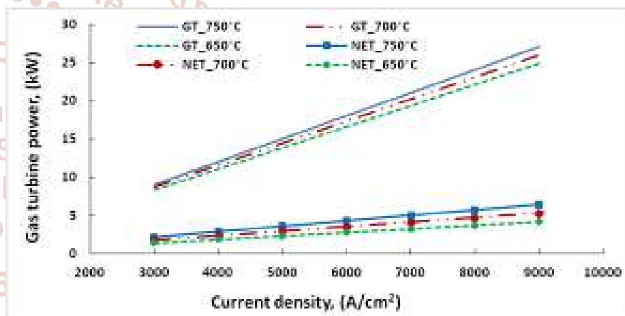

Figure5. Gas turbine power as a function of current density for three different temperatures

Fig. 6 shows the influence of current density on the exergy efficiencies of the SOFC stack and hybrid system for different operating temperature. As current density increases, the exergy efficiency decrease. However the increases in SOFC operating temperature causes an increase in the exergy efficiency of both SOFC stack and hybrid system as a result of an improvement of power output at high operating temperature. It is seen from the figure when the operation temperature increases from 600°C to 750°C at current density of 6000 A/cm², the exergy efficiency of the hybrid system increases from 60% to 66%.

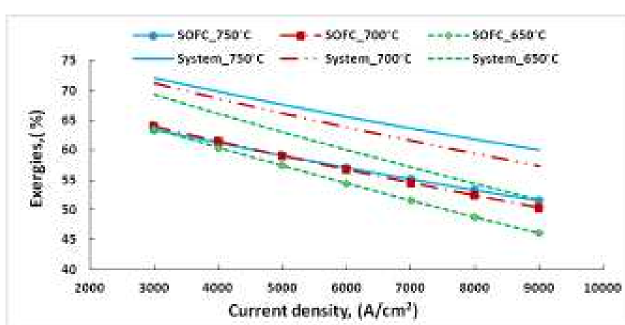

Figure6. Exergy efficiencies as a function of current density for three different temperatures

The effect of current density on the electrical efficiencies of the SOFC stack and hybrid system for different operating temperature indicates in Figure 7. The results showed that the electrical efficiency reduces as a current density increases and it enhances at high SOFC operating temperature. At current density of 6000 A/cm^2, the electrical efficiency of the hybrid system increase from 62% to 68%, and the electrical efficiency of the SOFC increase from 54.4% to 57% when the operation temperature increases from 600°C to 750°C.

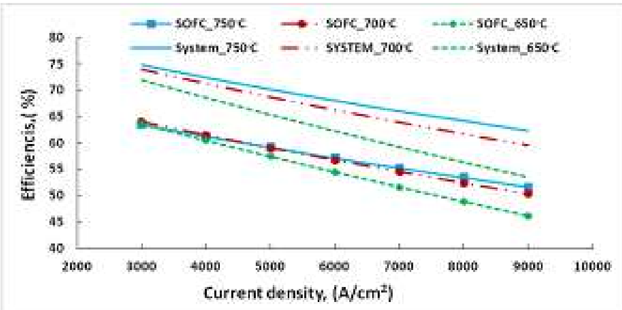

Figure7. Electrical efficiencies as a function of current density for three different temperatures

CONCLUSIONS

In the present study, a SOFC stack model based with internal reforming and integrated with gas turbine in a hybrid system are introduced. The effect of different SOFC operation temperatures on the power generated, efficiency, and exergy of the hybrid system were studied. The following main results were obtained:

- The cell voltage reduces with an increase in the current density while that the power density of SOFC stack, and the power output from the hybrid system increase with an increase in the SOFC operating temperature and current density.
- The GT power output increases with increasing of current density and SOFC operating temperature but more than 75% of the power output from the gas turbine is consumed by the auxiliary components.
- The increases in SOFC operating temperature causes an increase in the exergy efficiency of both SOFC stack and hybrid system as a result of an improvement of power output at high operating temperature.
- The electrical efficiency reduces as a current density increases and it enhances at high operating temperature of SOFC

NOMENCLATURE

A_{cell}	Cell area, (cm^2)
E_{ocv}	Fuel cell voltage at standard conditions, (V)
$\bar{e}_i^{kim}$	Standard chemical exergy of gases, (kJ/mol)
F	Faraday constant, (C/mol)
LHV	Lower heating value, (kJ/mol)
T_o	Ambient temperature, (K)
i	Current density in Ampere, ($A.\ cm^2$)
k	Specific heat ratio
n	Number of moles of electrons transferred
P_i	Partial pressure of gas, (Pa)
$\dot{W}$	Work transfer rate, (kW)
T	Absolute temperature, (K)
R	Universal gas constant, (J/mol K)
V_{stack}	Stack voltage, (V)
Greek Latters	
δ	Thickness, (cm)
η	Energy efficiency
ψ	Exergy efficiency
ρ	Electrical resistivity, (Ω^{-1} cm^{-1})
i_o	Exchange current density, (A cm^{-2})
Acronyms	
an	Anode
ca	Cathode
el	Electrolyte
int	Interconnection

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