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# Energy Analysis of Pressurized Solid Oxide Fuel Cell Combined Power Turbine

M. Ayazi, R. Karami, B. Kamkari

***Abstract*—**Solid oxide fuel cells have been considered in the last years as one of the most promising technologies for very high-efficiency electric energy generation from hydrogen or other hydrocarbons, both with simple fuel cell plants and with integrated gas turbine-fuel cell systems. In the present study, a detailed thermodynamic analysis has been carried out. Mass and exergy balances are performed not only for the whole plant but also for each component in order to evaluate the thermal efficiency of combined cycle. Moreover, different sources of irreversibilities within the SOFC stack have been discussed and a parametric study conducted to evaluate the effect of temperature as well as pressure on SOFC irreversibilities and its performance. In this investigation methane and hydrogen have been used for fueling the SOFC stack and combustion chamber.

***Keywords*—**SOFC, Energy, Power turbine, Irreversibility.

## I. Introduction

FINDING efficient power systems is of major concerns, especially with the depletion of fossil fuel sources with time. Energy demands are expected to keep increasing in the future. Thus, finding efficient systems is vital to reduce the unit of energy produced per the unit of fuel consumed. On the other hand, producing energy from fossil fuel causes some problem to the environment, such as global warming, air pollution, acid precipitation, ozone depletion, forest destruction and emission of radioactive substances, Dincer [1, 2]. For example, from 1990 to 2007 the CO2 equivalent emissions increased 17% in USA [3]. Therefore, finding efficient systems that produce less harmful emissions is crucial.

M. Ayazi is with Research Institute of Petroleum Industry (RIPI ). Energy Research center West Blvd., Near Azadi Sports Complex Tehran Iran Zip Code: 1485733111 (e-mail: Ayazim@ripi.ir).

R. Karami is with Research Institute of Petroleum Industry (RIPI ). Energy Research center West Blvd., Near Azadi Sports Complex, Tehran, Iran (e-mail: Karamir@ripi.ir).

B. Kamkari is with Research Institute of Petroleum Industry (RIPI ). Energy Research center West Blvd., Near Azadi Sports Complex Tehran Iran (e-mail: kamkarib@ripi.ir).

The efficiency of conventional power plants are usually less than 39%. That is, more than 60% of a plant's energy is lost. On the other hand, the overall efficiency of a conventional plant that produces electricity and heat separately is around 60% [4].

The Solid Oxide Fuel Cell (SOFC) is one of the most promising types of fuel cells. It is considered an excellent device for future power plants, expected to produce clean electrical energy at high conversion rates, low emissions and low noise levels [5], [6], and [7]. This electrochemical device is based on a solid-state ion-conducting ($O_2$) electrolyte (yttria-stabilized zirconia), which requires high operating temperature (up to 1000 °C). Such temperatures impose several technological constraints on SOFC materials, but make this device very suitable for co-generation or coupling with gas turbines (GTs). The integration of an SOFC stack with GTs and other conventional devices, such as compressors and heat exchangers, is a very successful application, since an SOFC–GT hybrid system can reach net electrical and global efficiencies close to 70% and 85%, respectively [8], [9] and [10]. In the last few years, many researchers were involved in the investigation of the SOFC stack and of the hybrid plant [11], [12] and [13]. A number of their papers simulated the performance of several types of SOFC–GT systems, analyzing their performance.

In this paper a parametric study on solid oxide fuel cell has been conducted and the effect of different parameters on SOFC performance has been discussed. Also total performance of combined solid oxide fuel cell and gas turbine with respect to pressure ratio discussed.

## II. System Description

The integrated GT–SOFC layout is schematically illustrated in Fig. 1. It is composed of six components: (1) air compressor, (2) recuperator, (3) high-temperature Solid Oxide Fuel Cell (SOFC), (4) combustor, (5) high pressure turbine (HPT) and (6) low pressure turbine (LPT). In the Proposed system air enters the cycle at state 1 through a compressor, where it is pressurized and then leaves at state 2.

**NOMENCLATURE**

| | | | |
|---|---|---|---|
| A | Constant appeared in $Eq.$ | $\dot{W}_{net}$ | Net power output of the plant, $kW$. |
| $A_c$ | Cell Area, $cm^2$ | *Greek letters* | |
| B | Constant that appears in $Eq.$ | $\Delta V_{loos}$ | Sum of the voltages looses due to irreversibilities. |
| E | Nernst potential or open circuit voltage, Volts. | $\eta$ | Efficiency. |
| $E^0$ | Ideal cell voltage at standard conditions, volts. | $\gamma$ | Ratio of specific heats. |
| F | Faraday constant. | $\lambda$ | Stoichiometric ratio. |
| H | Enthalpy, $KJ/Kg$. | *Superscript* | |
| I | Current, $mA$. | $cyc$ | Cycle |
| j | Current density, $mA/cm^2$. | *subscripts* | |
| $j_0$ | Exchange current density, $mA/cm^2$. | Act | Activation |
| $j_1$ | Limiting current density, $mA/cm^2$ . | C | Cell |
| LHV | Lower Heating value, $KJ/Kg$ . | comb | Combustor |
| $\dot{m}$ | Mass flow rate, $Kg/S$ . | conc | Concentration |
| P | Pressure, . | FC | Fuel cell |
| $\dot{Q}$ | Heat transfer rate, . | Gen | Generator |
| $\dot{Q}_{gen,FC}$ | Heating rate generated within the cell stack, $KW$. | GT | Gas Turbine |
| R | Universal gas Constance, $8.314/mole\ K$ . | in | Inlet |
| $r_p$ | Compression ratio. | invert | DC−AC inverter |
| T | Temperature, $K$. | ohm | Ohmic |
| $T_{sink}$ | Cold sink temperature, $K$. | out | Outlet |
| $U_f$ | Fuel utilization factor. | PT | Power turbine |
| V | Voltage, volts. | Recup | Recuperator |
| $\dot{W}$ | Power, $kW$. | th | Thermal |
| $\dot{W}_{FC,dc}$ | DC power output of the cell stack, $kW$. | | |

For GT power plants, preheating of air within a heat exchanger, such as a recuperator, by hot gases at the exhaust of the cycle improves the total efficiency of the system. Thus, air is preheated in the recuperator up to state 3, after which it enters the SOFC stack at the cathode side to participate in the electrochemical reaction. Since the electricity produced by SOFC stack is DC, an inverter is considered to convert it to AC. due to internal fuel cell irreversibilities–mainly ohmic resistances–heat is also generated to make temperatures of the reaction products rise up to state 4. Most of the mass flow rate of the fuel is not completely oxidized within the SOFC. It is assumed that this percentage of fuel will be burnt in the combustor, which is located, downstream of the SOFC.

Therefore, exit products from the stack (state 4) are further heated up to the desired temperature, such as state 5 in the combustor, due to direct combustion of fuel that is separately fed into the chamber. Then, the working gas carries a significant amount of thermal energy to drive the high pressure gas turbine, which provides the power requirement of the compressor, as shown in Fig. 1. It subsequently expands and drops in temperature until it leaves the GT at state 6. However, at this point, the working fluid still carries a higher amount of energy, which is able to drive the power turbine and produce further useful work, through further expansion of the working gas up to about atmospheric pressure (state 7). The heat of the exhaust gas is further utilized in the recuperator at relatively low compression ratios, to increase the temperature of the fresh air at the upstream side of the cell stack. Eventually, the exhaust working gas is discharged to the atmosphere at state 8.

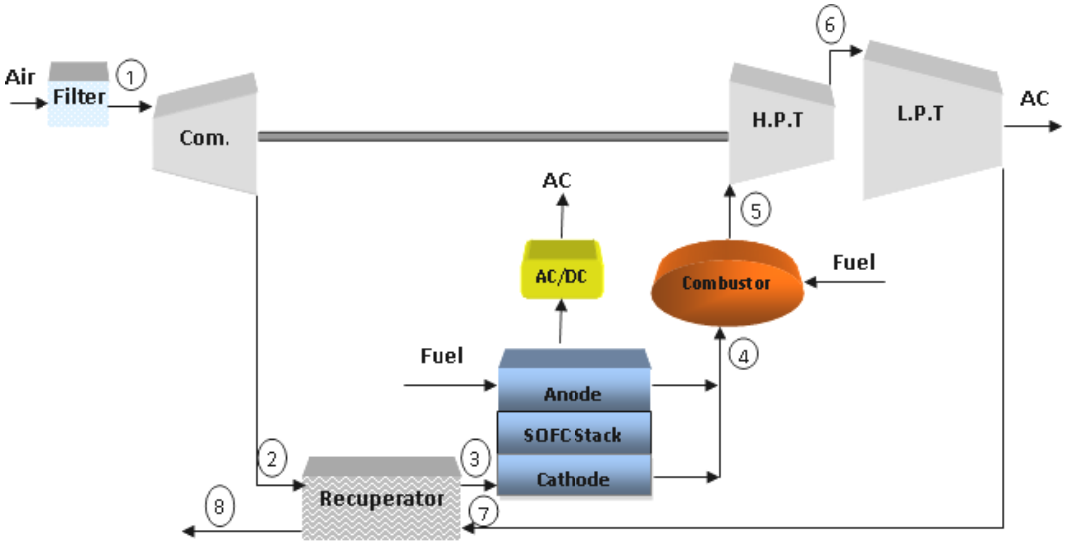


Fig. 1 Schematic of a combined Gas Turbine power plant with an SOFC

## III. Fuel Cell Irreversibilities

The actual cell potential is decreased from its ideal potential because of several types of irreversible losses. These losses are often referred to as polarization, overpotential or overvoltage, though only the ohmic losses actually behave as a resistance. Multiple phenomena contribute to irreversible losses in an actual fuel cell which will be discussed here.

### *A. Activation Losses*

These are caused by the slowness of the reactions taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons to or from the electrode.

In low- and medium-temperature fuel cells, activation overvoltage is the most important irreversibility and cause of voltage drop, and occurs mainly at the cathode. Activation overvoltage at both electrodes is important in cells using fuels other than hydrogen, such as methanol. At higher temperatures and pressures operational conditions such as pressurized solid oxide fuel cells the activation overvoltage becomes less important. Whether the voltage drop is significant at both electrodes and just the cathode, the size of the voltage drop is related to the current density, j by the equation:

$$\Delta V_{act} = Aln(\frac{j+j_n}{j_0}) \quad (1)$$

Where

$j_n$: is the internal and fuel crossover equivalent current density and is negligible for solid oxide fuel cells

$A$ : depends on the electrode and cell conditions which is the slope of the Tafel line and is equal with 0.002

$j_0$ : is exchange current density

### *B. Fuel Crossover and Internal Losses*

Fuel crossover is a phenomenon that takes place when a certain amount of fuel diffuses from the anode to the cathode, through electrolyte, without reacting electrochemically. At the cathode electrode, it reacts directly with oxygen producing heat. Moreover, the real electrolytes are usually very good ionic conductors, even if they could also support some electron conduction, determining the internal currents. Both phenomena determine voltage losses. In the first case, some fuel is combusted and in the second, electrons cannot be used by the external electrical load. They are summarized in a single loss, called 'mixed potential', introducing the internal current density in. This loss is usually neglected in case of solid oxide fuel cell.

### *C. Ohmic Losses*

The losses due to the electrical resistance of the electrodes, and the resistance to the flow of ions in the electrolyte, are the simplest to understand and to model. SOFCs are greatly affected by this kind of loss because of their physical configuration. The voltage drop is due to the ohmic resistance of cathode, anode, electrolyte and mostly interconnections. The total ohmic loss is evaluated using the following formula:

$$\Delta V_{ohm} = jr \quad (2)$$

The area-specific resistance (r) depends on material thickness and the SOFC operating temperature because of the resistivity exponential dependence.

### *D. Mass Transport and Concentration Losses*

If the oxygen at the cathode of a fuel cell is supplied in the form of air, then it is selfevident that during fuel cell operation there will be a slight reduction in the concentration of the oxygen in the region of the electrode, as the oxygen is extracted. The extent of this change in concentration will depend on the current being taken from the fuel cell, and on

physical factors relating to how well the air around the cathode can circulate, and how quickly the oxygen can be replenished. This change in concentration will cause a reduction in the partial pressure of the oxygen.

Similarly, if the anode of a fuel cell is supplied with hydrogen, then there will be a slight drop in pressure if the hydrogen is consumed as a result of a current being drawn from the cell. This reduction in pressure results from the fact that there will be a flow of hydrogen down the supply ducts and tubes, and this flow will result in a pressure drop due to their fluid resistance. This reduction in pressure will depend on the electric current from the cell (and hence $H_2$ consumption) and the physical characteristics of the hydrogen supply system. In both cases, the reduction in gas pressure will result in a reduction in voltage. Following equation gives a very good fit to the results, provided the constants *m* and *n* are chosen properly.

$$\Delta V_{trans} = m\, exp(nj) \tag{3}$$

*E. Total Voltage Losees*

All the voltage losses listed earlier are summarized using a single formula that accounts for all the described phenomena:

$$V = E_{oc} - jr - Aln(j) + m\, exp(nj) \tag{4}$$

Constants values in the above equation for a high temperature solid oxide fuel cell are given Table I.

TABLE I
CONSTANT OPERATING PARAMETERS OF SOFC

| | |
|---|---|
| $E_{oc}\ (V)$ | 1.01 |
| $r\ (k\Omega\ cm^2)$ | $2.0 \times 10^{-3}$ |
| $A\ (V)$ | 0.002 |
| $m\ (V)$ | $1.0 \times 10^{-4}$ |
| $n\ (cm^2 mA^{-1})$ | $8 \times 10^{-3}$ |

*F. Effect of Temperature and Pressure*

The thermodynamic efficiency of SOFCs operating on $H_2$ and $O_2$ at open circuit voltage is lower than that of other low temperature fuel cells because of the lower free energy at higher temperatures. On the other hand, the higher operating temperature of SOFCs is beneficial in reducing polarization resistance. The dependence of SOFC performance on temperature is expressed by the following equation:

$$\Delta V_T(mV) = 0.008\ (T_2 - T_1) \tag{5}$$

SOFCs, like other fuel cells, show enhanced performance by increasing cell pressure. The following equation approximates the effect of pressure on cell performance.

$$\Delta V_p(mV) = 59 \ln\left(\frac{P_2}{P_1}\right) \tag{6}$$

Where $P_1$ and $P_2$ are different cell pressures. The above correlation was based on the assumption that overpotentials are predominately affected by gas pressures and that these overpotentials decrease with increased pressure.

## IV. ENERGY FORMULATION OF COMPONENTS

The thermodynamic performance of each of the components introduced in the preceding section will be analyzed here. The mass and energy balance are employed under the assumption of steady flow for the entire cycle. The main stream of the working fluid assumed as ideal gas, at different states of the cycle is shown in Fig. 1.

*A. Compressor*

The isentropic efficiency of the compressor is defined as:

$$\eta_c = \frac{w_{cs}}{w_{ca}} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{7}$$

Where the ideal temperature of the working fluid at the outlet of the compressor can be determined using the following equality.

$$\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma} \tag{8}$$

Applying the energy balance for the system, one may find the following work required for the compressor to produce a compression ratio of $r_p$.

$$\dot{w}_c = \dot{m}_1(h_2 - h_1) \tag{9}$$

*B. Recuperator*

The effectiveness of the recuperator is described as:

$$\varepsilon_{recup} = \frac{T_3 - T_2}{T_7 - T_2} \tag{10}$$

Using the following energy balance equation, one may find the outlet temperature of the cycle:

$$\dot{m}_2(h_3 - h_2) = \dot{m}_7(h_7 - h_8) \tag{11}$$

*C. Solid Oxide Fuel Cell*

The fuel utilized to supply the system is methane ($CH_4$), with a lower heating value of 50,050 kJ/kg. The following electrochemical reactions occur within the anode and cathode of the fuel cell:

In this investigation methane and hydrogen have been used for fueling the SOFC stack and combustion chamber.

In the anode the following electrochemical reaction occurs:

$$H_2 + O^= \rightarrow H_2O + 2e^-$$
$$CO + O^= \rightarrow CO_2 + 2e^-$$
$$CH_4 + 4O^= \rightarrow 2H_2O \rightarrow +CO_2 + 8e^- \tag{12}$$

And for the anode side:

$$\tfrac{1}{2}O_2 + 2e^- \rightarrow O^= \tag{13}$$

The degree to which an anode supports direct oxidation will then impact the degree of prereforming of the fuel that is required, which in turn typically impacts the balance of plant complexity and cost [33].

The net cell reaction is thus written as:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{14}$$

And the net cell reaction for hydrogen as fuel is as following:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (15)$$

The solution of the overall mass and energy balances of the fuel cell requires the evaluation of both the voltage and the current produced by the stack. The reversible cell voltage, E, is defined by the Nernst equation as follows:

$$E = E^0 + \frac{RT}{8f} ln\left(\frac{P_{CH_4}P_{O_2}^2}{P_{CO_2}P_{H_2O}^2}\right) \quad (16)$$

where $E_0$ is the ideal cell voltage at standard conditions (i.e., 298.15 K and 1 bar), R is the universal gas constant, T is the stack temperature, and F denotes the Faraday constant (96,485 C/ mole).The Nernst equation provides a relationship between the ideal standard potential, E0, for the cell reaction and the ideal equilibrium potential, E, at other temperatures and partial pressures of reactants and products. By defining the current density, j, as the rate of electron transfer per unit activation area of the fuel cell, the DC electric power produced by the fuel cell can be expressed by:

$$\dot{W}_{FC,dc} = V_c j A_c \quad (17)$$

Where $V_c$ represents the cell voltage. This is the difference between the open-circuit voltage, obtained from the Nernst equation, and voltage losses in the fuel cell:

$$V_c = E - \Delta V_{loos} \quad (18)$$

Where $\Delta V_{Loss}$ is the sum of the voltage losses due to irreversibilities in the fuel cell, which include activation polarization, ohmic losses and concentration losses obtained by summation of equations 1-3.

Each of the irreversibilites which mentioned in eq. 16 can be obtained using following equations.

Some heat generation occurs within the cell stack, due to the irreversibilities mentioned earlier. The following equation may be used to determine the rate of heat generated within the cell stack.

$$\dot{Q}_{gen,FC} = I\,\Delta V_{Loos} = jA_c(E - V_c) \times 10^{-6}[KW] \quad (19)$$

The oxygen used in the reaction of Eq. (12) will be normally derived from air. The airflow is usually well above the stoichiometric amount, typically twice higher. If the stoichiometric ratio is l, then the following equation gives the mass flow rate of air usage:

$$\text{Air usage} = 3.75 \times 10^{-7} \times \lambda \times \frac{\dot{W}_{FC,dc}}{V_c}\ [\text{Kg/s}] \quad (20)$$

The mass balance for this system gives:

$$\sum_{in} mass\ flows = \sum_{out} mass\ flowss \quad (21)$$

Thus,

$$\dot{m}_3 + \dot{m}_{fuel,FC} = \dot{m}_4 + \dot{m}_{fuel,FC} \times (1 - U_f) \quad (22)$$

Where $U_f$ denotes the fuel utilization factor. The last term on the right side of the above equality represents the non-reacted mass flow rate that leaves the fuel cell downstream of the products. Applying the first law of thermodynamics to the SOFC and assuming an adiabatic process,

$$\dot{m}_3 h_3 + \dot{m}_{fuel,FC} \times U_f \times LHV + m_{fuel,FC} \times (1 - U_f) h_{fuel,in} - \dot{W}_{FC,dc} - \dot{m}_4 h_4 = 0 \quad (23)$$

Where LHV is the lower heating value of the fuel.

*D. Cumbustor*

The working fluid of the cycle, with products from the fuel cell, is further heated within the combustor. Considering that non-reacted flow of fuel from the SOFC is burnt in the combustor, the mass balance of the combustor yields:

$$(\dot{m}_3 + \dot{m}_{fuel,FC}U_f) + \dot{m}_{fuel,FC}(1 - U_f) + \dot{m}_{fuel,comb} = \dot{m}_4 + \dot{m}_{fuel,comb} = \dot{m}_5 \quad (24)$$

The first law of thermodynamics for the combustor can be expressed as:

$$(\dot{m}_3 + U_f \times \dot{m}_{fuel,FC})h_4 + \dot{Q}_{comb} - \dot{m}_5 h_5 - \dot{Q}_{loos} = 0 \quad (25)$$

Where

And $\eta_{comb}$ represents the efficiency of the combustor.

$$\dot{Q}_{comb} = \left[\dot{m}_{fuel,FC} \times (1 - U_f) + \dot{m}_{fuel,comb}\right] \times LHV \quad (26)$$

$$\dot{Q}_{loos} = \left[\dot{m}_{fuel,FC} \times (1 - U_f) + \dot{m}_{fuel,comb}\right] \times (1 - \eta_{comb}) \times LHV \quad (27)$$

*E. Gas Turbine*

As shown in Fig. 1, the required work of the compressor is provided by the high pressure gas turbine:

$$\dot{W}_{GT} = \dot{W}_C \quad (28)$$

Knowing the turbine inlet temperature (TIT), the outlet temperature of the turbine, $T_6$, can be determined. Furthermore, through the definition of isentropic efficiency of the turbine,

$$\eta_{GT} = \frac{W_{GTa}}{W_{GTs}} = \frac{h_5 - h_6}{h_5 - h_{6s}} \quad (29)$$

The ideal temperature of the working gas at the outlet of the turbine can be evaluated. Therefore, using Eq. (37), the downstream pressure of the gas turbine is determined as:

$$P_6 = P_5 \left(\frac{T_{6s}}{T_5}\right)^{\gamma/(\gamma-1)} \quad (30)$$

*F. Power Turbine*

The relevant governing equations for the power turbine are similar to those presented in the previous section. Considering the isentropic efficiency of the turbine, the downstream temperature of the power turbine, $T_7$, may be determined from

$$\eta_{PT} = \frac{W_{PTa}}{W_{PTs}} = \frac{h_6 - h_7}{h_6 - h_{7s}} \quad (31)$$

Where the ideal temperature of the working fluid at the outlet of the turbine can be evaluated using:

$$T_{7s} = T_6 \left(\frac{P_7}{P_6}\right)^{(\gamma-1)/\gamma} \quad (32)$$

The amount of work transmitted to the generator is calculated as:

$$\dot{W}_{PT} = \dot{m}_6(h_6 - h_7) \quad (33)$$

*G. Overall Balance Equations for Integrated Cycle*

The integrated Gas–Turbine power plant with an SOFC in Fig. 1 may be analyzed as a lumped control volume. In the following mass balance as well as the first and second laws of thermodynamic will be derived for this control volume.

1. Mass Balance

The mass balance for the system is written as:

$$\dot{m}_1 + \dot{m}_{fuel} - \dot{m}_8 = 0 \quad (34)$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 \quad (35)$$

$$\dot{m}_{fuel} = \dot{m}_{fuel,FC} + \dot{m}_{fuel,comb} \quad (36)$$

$$\dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8 \quad (37)$$

TABLE II
MAIN OPERATING PARAMETERS OF THE GT-SOFC PLANT

| | |
|---|---|
| *Gas turbine cycle* | |
| Compressor efficiency ($\eta_{comp}$) | 0.81 |
| Turbine efficiency ($\eta_{GT}$) | 0.84 |
| Power turbine efficiency ($\eta_{PT}$) | 0.89 |
| Recuperator effectiveness ($\eta_{Recup}$) | 0.8 |
| Combustor efficiency ($\eta_{Comb}$) | 0.98 |
| AC generator efficiency ($\eta_{Gen}$) | 0.95 |
| *Solid oxide fuel cell* | |
| Air utilization factor ($U_a$) | 0.25 |
| Fuel utilization factor ($U_f$) | 0.85 |
| Stack temperature ($T_{stack}$) (K) | 1273 |
| Current density (A/cm$^2$) | 0.3 |
| DC–AC inverter efficiency ($\eta_{invert}$) | 0.89 |
| Cell area (cm$^2$) | 834 |
| *Pressure losses* | |
| Recuperator gas/air sides (%) | 4 |
| Fuel cell stack (%) | 4 |
| Combustor (%) | 5 |
| *Ambient conditions* | |
| Temperature (K) | 288 |
| Pressure (atm) | 1 |

2. Energy Balance

The overall energy balance of the system gives:

$$\dot{m}_1 h_1 + \dot{m}_{fuel,FC} \times U_f \times LHV_{CH_4} + \dot{Q}_{comb} - \dot{m}_8 h_8 - \dot{Q}_{loos} - \dot{W}_{FC,dc} - \dot{W}_{pT} = 0 \quad (38)$$

Where $\dot{Q}_{comb}$ and $\dot{Q}_{loos}$ are previously defined in Eqs. (31) and (32), respectively. The total thermal efficiency of the GT–SOFC plant is defined as the ratio of the net work output to the total rate of energy input to the system.

$$\eta_{th}^{cyc} = \frac{\dot{W}_{net}}{\dot{Q}_{tot}} \quad (39)$$

Where:

$$\dot{W}_{net} = \dot{W}_{FC,ac} + \dot{W}_{Gen} \quad (40)$$

$$\dot{W}_{FC,ac} = \eta_{invert}\dot{W}_{FC,dc} \quad (41)$$

$$\dot{W}_{Gen} = \eta_{Gen}\dot{W}_{PT} \quad (42)$$

$$\dot{Q}_{tot} = \dot{m}_{fuel,FC} \times U_f \times LHV_{CH_4} + \dot{Q}_{comb} \quad (43)$$

Here, $\eta_{invert}$ denotes the DC–AC inverter efficiency and $\eta_{Gen}$ represents the AC generator efficiency.

The cycle operational condition is listed in Table II.

## V. THERMOCHEMICAL AND GT-SOFC RESULTS

The performance of a fuel cell stack is usually described by plotting the polarization curve, which relates the cell voltage to its current density. This plot is affected by all the typical losses of the fuel cell under investigation and can be used to analyze their values. The polarization curve of the SOFC used in the study is represented in Fig. 2 and 3.

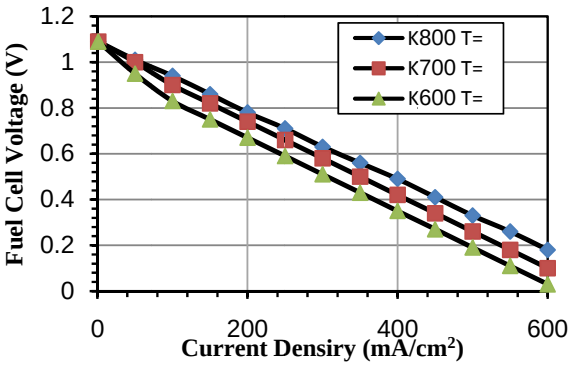


Fig. 2 Fuel cell voltage versus current density for various temperatures

Fig. 2 clearly shows the strong dependence of the SOFC voltage on its operating temperature by effecting the electrode reaction rate and ohmic losses. As it shown by increasing the current density, fuel cell voltage decreases which is the result of growing of irreversibility's discussed before.

According to the Nernst equation, it can be observed that the cell voltage value increases by raising the operating pressure (Fig. 3). Moreover, by increasing cell operating pressure, it is possible to gain best performance even if a higher cost must be taken into account, due to the energy and investment for compressors.

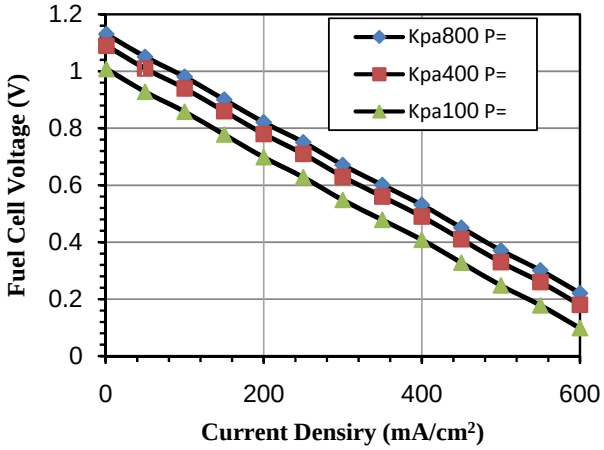


Fig. 3 Fuel cell voltage versus current density for various working pressure

The shape of SOFC polarization curve depends on the Ohmic, concentration and activation losses. Results showed that the first and the last one are dominant in the overall overvoltage. The Ohmic losses (Fig. 4) affecting the SOFC are mainly due to interconnections among cathode, anode and electrolyte. This kind of overvoltage could be reduced by lowering the cell thickness or by increasing the operating temperature as shown in Fig. 4. The impact of temperature on cell resistance is different for different materials. For metals, the resistance usually increases with temperature, while for electronically and ionically conductive ceramics which are mainly used as anode and cathode it decreases exponentially.

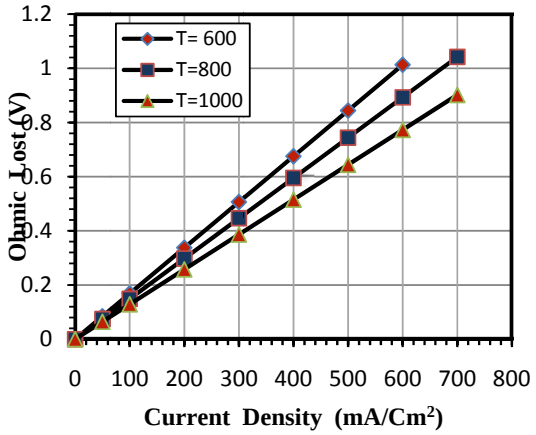


Fig. 4 Ohmic voltage lost versus current density for various temperatures

Fig. 5 shows that the concentration loss increases by increasing current density with an exponential trend. Finally, Fig. 6 shows the activation loss that consists mainly of cathode activation overpotential, due to an exchange current value much greater than the anode one.

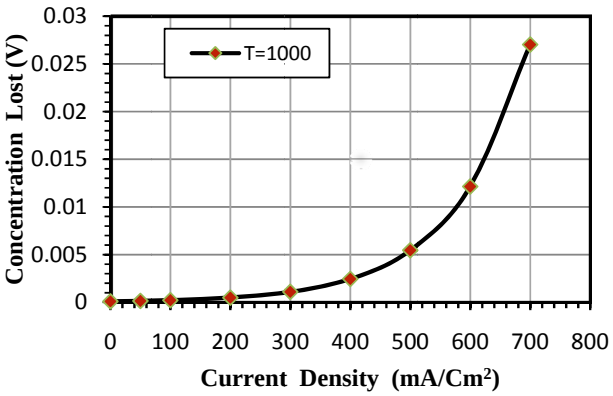


Fig. 5 Concentration lost versus current density

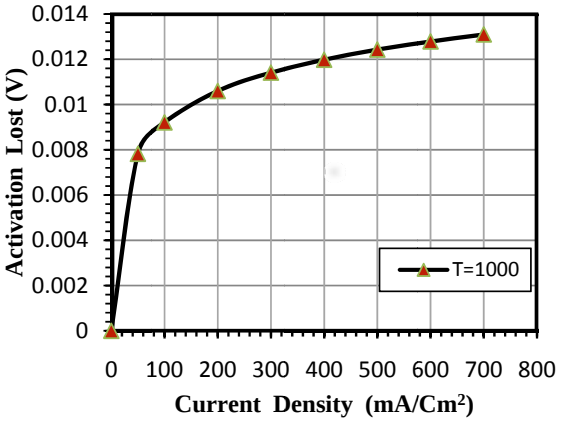


Fig. 6 Activation lost versus current density

Fig. 7 shows SOFC stack power generation rate versus fuel flow rate for methane as fuel. It can be deduced that there is an optimum value for fuel rate which increasing the fuel rate more than that will result in a reverse effect on power generation. This phenomenon can be explained by increasing the voltage lost when more current produced by SOFC stack. As it was expected increasing the temperature leads to more power generation.

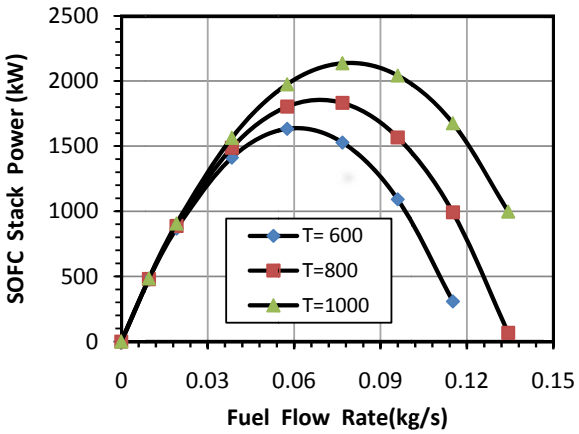


Fig. 7 SOFC stack power generation rate versus fuel flow rate for various temperature

It should be noted that each fuel cell stacks consists of many single fuel cells which air and fuel flows through the channel of fuel cells. If more power is desirable, the number of cells in a SOFC should increase. Fig. 8 shows the effect of increase of the net reacting surface on total power generation by the SOFC stack. As it is illustrated increase the net reacting surface and temperature lead to higher power generation.

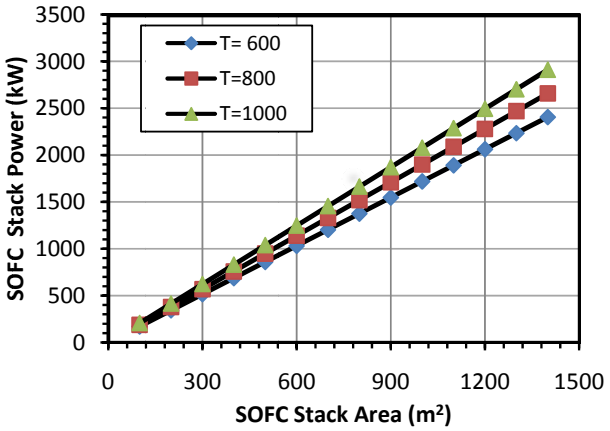


Fig. 8 SOFC stack power generation rate versus active area of SOFC stack for various temperature

In order to investigate the effect of fuel type on SOFC power generation rate, hydrogen as well as methane has been considered. Fig. 9 illustrates the net power generation rate by each fuel of hydrogen and methane. As it's obvious, hydrogen shows more power generation rate than methane at the same fuel flow rate. The superior of hydrogen comes from its higher latent heat value. On the other hand, as stated before there are optimum values of fuel flow rates for both hydrogen and methane which passing these optimum values lead to decrease of the power generation rate.

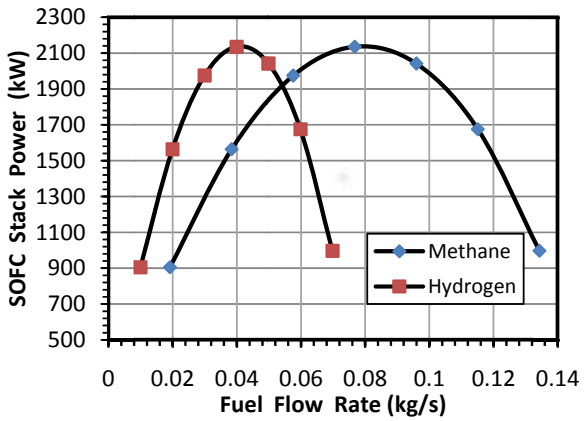


Fig. 9 SOFC stack power generation rate versus fuel flow rate for hydrogen and methane as fuel

Fig. 10 shows fuel flow rate versus current density. As it's shown for a fixed current density the rate of hydrogen usage is less than methane usage.

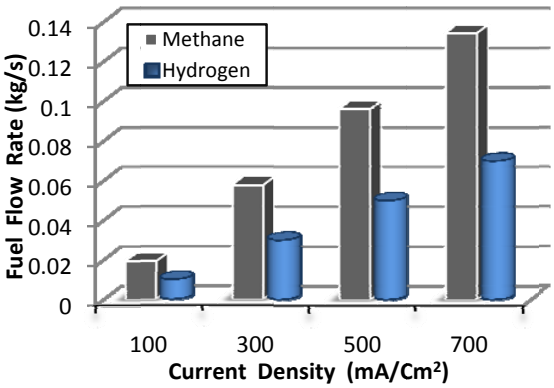


Fig. 10 Fuel flow rate versus current density for hydrogen and methane as fuel

As it is shown in Fig. 11, it can be seen that thermal efficiency of a GT-SOFC is considerably higher than the conventional GT plant. In the conventional GT plant, the majority of irreversibility takes place in the combustor, where a large amount of heat is transferred to the working fluid, due to direct burning of the fuel. In the GT–SOFC cycle, the irreversibility within the combustor is lower, compared to a conventional plant. Nevertheless, there exists one more component, a fuel cell stack, which produces a significant rate of irreversibility, due to the chemical reaction internally and consequently causes the working fluid to be preheated before entering the combustor, as well as a considerable amount of power production. Both factors lead to higher energetic efficiency, compared to the conventional plant. The power requirement of a compressor in the GT plant is higher, provided both cycles operate at their optimum point, thereby having a negative role with respect to efficiency of the cycle, compared to the GT– SOFC cycle. On the other hand, it could be deduce from Fig. 11 that thermal efficiency of GT_SOFC cycle increase with increasing the compression ratio up to an optimum ratio of 4 and then it shows a descending trend.

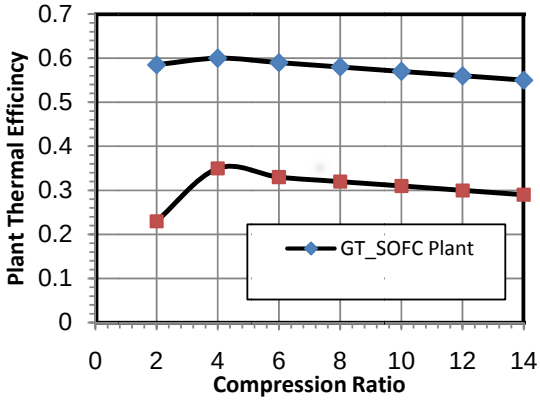


Fig. 11 Comparison of the thermal efficiency versus compression ratios, between a conventional GT plant and GT-SOFC plant

The environmental impact in terms of $CO_2$ emissions was also studied in the current paper. The predicted $CO_2$ emissions of GT and GT–SOFC cycles are illustrated in Fig. 12 with respect to various compression ratios. This figure reveals the environmental friendly performance of GT–SOFC, compared to a conventional GT plant, since the efficiency of the modern cycle is significantly higher than that of GT plant.

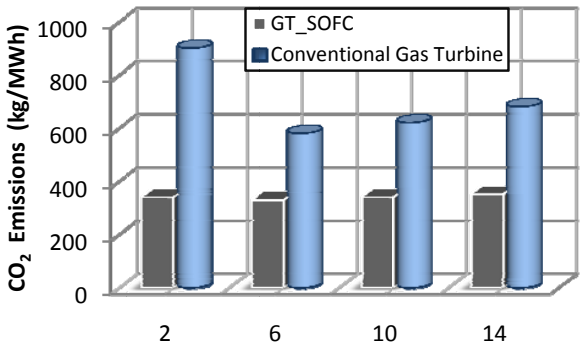


Fig. 12 Comparison of carbon dioxide emissions versus compression ratio between Gas Turbine plant without SOFC (conventional plant) and with SOFC (GT–SOFC plant) at the same operating condition

## VI. Conclusion

In this paper a thermodynamic analysis has been carried out to investigate the SOFC performance as well as its irreversibilities. It concluded that the voltage losses in SOFCs are governed by ohmic losses in the cell components and contribution of two other irreversibilities- activation and overpotantial- to the total voltage lost are much less than ohmic lost. The parametric analysis of the stack behavior, based on a variation of the cell operating parameters such as temperature and pressure, yields a detailed insight on the influence of each variable on the cell efficiency and electric power output. This investigation reveals that there are optimum values for current density for both hydrogen and methane which taking over this values result in decease of power generation rate. Also, the GT–SOFC power plant is more efficient than a traditional GT plant, by as much as 28% with respect to the thermal efficiency and less $CO_2$ emission.

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