

Thermodynamic Analysis of a Hybrid Solid Oxide Fuel Cell-Gas Turbine Power Plant

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Abstract: Nowadays utilization of highly efficient and low pollutant power production systems is one of the primacies and attractive topics for researchers. Solid oxide fuel cells are such systems; and their capabilities to integrate with power cycles such as gas turbine cycles propose a hybrid system for future power plant. This study examines the performance of a natural-gas-fed tubular solid-oxide fuel cell combined with a conventional recuperative gas turbine power plant. The overall system performance is analyzed by analyzing all components separately. Also a parametric study was performed to investigate the effect of various parameters such as compressor Pressure ratio and fuel mass flow rate on the cycle exergy performance, entropy generation rate, SOFC power, electrical power and CO₂ emission. The results revealed that it is possible for this system to reach a first law efficiency more than 61%.

Key words: SOFC • Hybrid system • Gas turbine • Fuel cell • Entropy generation • First law

INTRODUCTION

Due to the growing energy consumption of the world and its environmental effect, utilization of highly efficient and low pollutant power production systems is one of the primacies and attractive topics for researchers. Fuel cells, as an alternative to conventional energy-conversion systems, have the prospect for exploiting fossil fuels more efficiently. Among the different types, solid oxide fuel cell (SOFC) technology is very promising because of its high efficiency, less polluting, fuel flexibility and high temperature of the exhaust heat which can be used for cogeneration or bottoming cycles for additional electricity generation [1]. Therefore technology of combined SOFC and gas turbine (SOFC/GT) systems have attracted increasing interest universally and is being further investigated by researchers due to its superior technology and high efficiency and its capability of using both fossil and renewable fuels.

Siemens-Westinghouse Power Company developed the first tubular SOFCs for a variety of applications in stationary power generation market. By pressurizing a SOFC and integrating it with a gas turbine (PSOFC/GT), power systems with efficiencies as high as 70-75% could be obtained [2]. Chan *et al.* [3, 4] modelled a simple SOFC and GT power plant and showed that an internal-reforming hybrid SOFC/GT system could achieve an

electrical efficiency of more than 60% and a system efficiency including waste heat recovery for co-generation of more than 80%. Kuchonthara *et al.* [5] studied energy recovery in SOFC and GT combined system using simulation software ASPEN Plus. Palson [6] and Selimovic [7] carried out a comprehensive examination of hybrid SOFC and GT systems. Song *et al.* [8] investigated the possible extension of a SOFC/GT hybrid system to multi-MW power station based on a commercially available gas turbine and other thermo-economic analyses of SOFC/GT hybrid systems. Also SOFC were analysed by Calise *et al.* [9-12]. Finally Zhang *et al.* [13] reviewed integration strategies for SOFCs.

These investigations were generally based on the first law of thermodynamics and didn't spot the second law of thermodynamics. The first-law merely serves as a necessary tool for the bookkeeping of energy during a process and offers no challenges to the engineer. The second law, however, deals with the quality of energy. More specifically, it is concerned with the degradation of energy during a process, the entropy generation and the lost opportunities to do work. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems [14]. However, a full study on literature shows that there are a few papers that investigated performance of systems including SOFC/GT through the second law of thermodynamics [9-12].

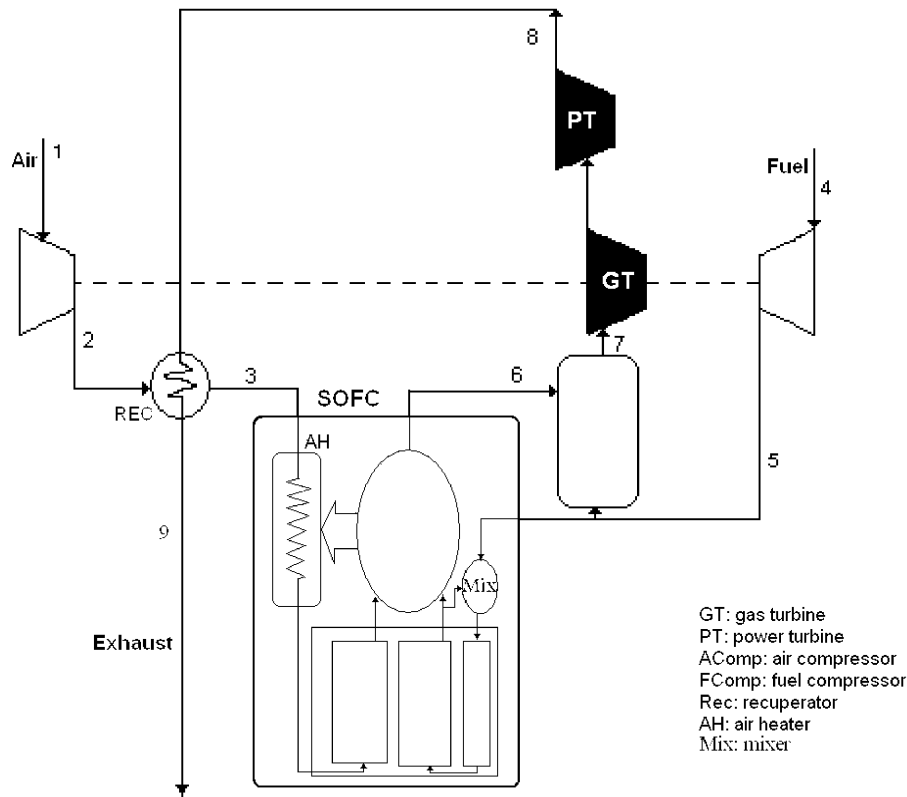


Fig. 1: layout of SOFC/GT hybrid system with recuperator

Granovskii *et al.* [15] compared the performance of two Combined SOFC-Gas Turbine Systems. Bavarsad [16] performed an energy and exergy analysis of an internal reforming solid oxide fuel cell-gas turbine hybrid system. A thermodynamic analysis of a combined gas turbine power system with a solid oxide fuel cell was carried out through exergy analysis by Haseli *et al.* [17]. Moreover, Motahar and Alemrajabi [18] investigated an SOFC/GT hybrid system equipped with a steam injection system. Also, Haseli *et al.* [19] performed an entropy generation analysis of SOFC/GT hybrid systems. Effect of design parameters on the exergetic operation of gas-turbine power plants was investigated by Goodarzi and Shobi [20].

The aim of the present work is to propose a novel SOFC/GT hybrid cycle to improve the efficiency of the conventional gas turbine cycles. For this purpose, the proposed SOFC/GT hybrid system is simulated and analyzed and the cycle performance including entropy generation rate and CO₂ emission is investigated. Also a parametric study is performed to study the effect of various parameters such as compressor Pressure ratio and fuel mass flow rate on entropy generation rate, SOFC power, electrical power and CO₂ emission.

System Description: Layout of the hybrid cycle of solid oxide fuel cell and gas turbine (SOFC/GT) hybrid system with recuperator which is considered in this study is shown in Fig. 1.

This system is fed by natural gas whose chemical composition is 1.5% nitrogen, 1.5% carbon dioxide and 97% methane. Chemical composition of atmospheric air is considered to be 21% oxygen and 79% nitrogen. The SOFC/GT hybrid system is composed of an SOFC stack, a combustion chamber, a GT and a power turbine (PT), a fuel compressor (FComp), an air compressor (AComp) and a recuperator.

Ambient air at point 1 is entered to the cycle and compressed by the AComp up to point 2. Then the air is preheated in the recuperator (RE) and air heater (AH) and then it is passed to the cathode inlet of the SOFC stack. Similarly, the fuel at point 4 is entered and compressed by the FComp up to point 5 and then passed to the anode inlet of the SOFC stack. In the SOFC stack, the natural gas internal reforming reaction is done and hydrogen-rich products are produced. The steam essential for the reforming reaction is supplied through the anode gas recirculation. Reformed fuel enters the anode flow of the fuel cell and reacts electrochemically with the cathode

flow and produces electric power. The electrochemical reaction occurs at the three-phase boundaries (TPB) of both electrodes and produces ionic flow through the electrolyte and electron flow across the electrodes. Electrical work is hence produced together with heat generation. The generated heat is partly dissipated to the environment, partly used to reform the natural gas and partly used to heat up the feedstock and effluent gases [3]. The outlet air of SOFC stack and fuel react in the combustion chamber. Combustion products at point 7 are entered into the gas turbine and produce mechanical work. This mechanical work is used to drive the AComp and FComp. The outlet stream from the GT enters the PT and its outlet stream is fed into the recuperator.

System Modeling: Assuming that the processes are steady-state, the first law and second law of thermodynamics can be applied to predict the performance of all components as well as the overall system.

Air Compressor: The isothermal efficiency of air compressor is defined as:

$$\eta_{isoth,ac} = \frac{W_{cs}}{W_{ca}} = \frac{R_u T_1 \ln(r_p)}{h_2 - h_1} \quad (1)$$

Where:

T_1 is the inlet temperature of AComp and r_p is the pressure ratio of the compressor. One can use this equation to calculate the actual outlet temperature of AComp.

By applying the energy balance on the AComp control volume, actual power consumption and entropy generation rate of AComp are calculated as:

$$\dot{Q}_{surr,ac} = \dot{n}_1(s_2 - s_1) \cdot \frac{T_1 + T_2}{2} \quad (2)$$

$$\dot{S}_{gen,ac} = \dot{n}_1(s_2 - s_1) - \frac{\dot{Q}_{surr,ac}}{T_1} \quad (3)$$

Similar calculations may be performed for the fuel compressor (FComp).

Recuperator: Using ϵ -NTU method, calculation of heat transfer between cold and hot fluids can be performed for the counter-flow recuperator, RE. The effectiveness of RE is defined as:

$$\epsilon_{Rec} = \frac{T_3 - T_2}{T_8 - T_2} \quad (4)$$

And energy balance for RE may be written as:

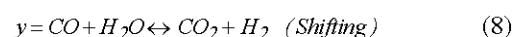
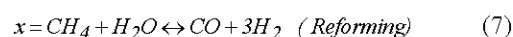
$$\dot{n}_2(h_3 - h_2) = \dot{n}_8(h_8 - h_9) \quad (5)$$

Therefore entropy generation rate can be calculated as:

$$\dot{S}_{gen,Rec} = \dot{n}_2(s_3 - s_2) - \dot{n}_8(s_8 - s_9) \quad (6)$$

Solid Oxide Fuel Cell: The SOFC model developed in this study is based on tubular design which is assumed to be fed by the natural gas and its geometric and performance related data are based on the design developed and reported by [21].

Chemical Reactions: Chemical reactions for internal reforming of methane and shifting of water are assumed to be as following [19]:



Where:

x , y and z are the molar flow rates of the reactions. The equilibrium constants of reforming and shifting processes are temperature-dependent and can be obtained from the following equation:

$$\log K_p = AT^4 + BT^3 + CT^2 + DT + E \quad (10)$$

Where:

A, B, C, D and E are constant [16].

Having calculated x , y and z , the equilibrium constants can be written as follows:

$$K_{pr} = \frac{\left(([CO]^i + x - y) ([H_2]^i + 3x + y - z)^3 \right)}{\left(([CH_4]^i - x) ([H_2O]^i - x - y - z) \right) (n_t^i + 2x)^2} P_{cell}^2 \quad (11)$$

$$K_{psh} = \frac{\left(([CO_2]^i + y) ([H_2]^i + 3x + y - z) \right)}{\left(([CO]^i + x - y) ([H_2O]^i - x - y - z) \right)} \quad (12)$$

$$Z = U_f(3x + y) \quad (13)$$

Where:

U_f is the fuel utilization rate. Since the equilibrium constants depend on partial pressures and partial pressures depend on flow molar rate of each species, when the temperature is determined, the equilibrium

constants can be calculated from Eq. (10) and the unknown x, y and z are determined by solving Eqs. (11), (12) and (13) simultaneously for the specified fuel utilization rate and inlet conditions of the flow.

Since both reforming and shifting reactions are endothermic; the heat needed for each reaction can be calculated as follows:

$$Q_r = x(h_{CO} + h_{H_2} - h_{H_2O} - h_{CH_4}) \quad (14)$$

$$Q_{sh} = y(h_{CO_2} + h_{H_2} - h_{H_2O} - h_{CO}) \quad (15)$$

Assuming that released heat of electrochemical reaction is Q_{rxn} , total heat transfer of SOFC would be:

$$Q = Q_{rxn} - Q_r - Q_{sh} \quad (16)$$

Potential of SOFC: The actual potential of a fuel cell would be:

$$E = E_{re} - (\eta_{act} - \eta_{ohm} - \eta_{conc}) \quad (17)$$

Where:

E_{re} is the ideal reversible potential of the cell, η_{act} , η_{ohm} and η_{conc} are activation overpotential, ohmic overpotential and concentration overpotential, respectively which can be calculated easily [3].

Temperature of SOFC: Writing energy balance over the control volume of SOFC, the temperature of SOFC can be calculated by an iterative computational method [3]:

$$Q_{error} = \left| \frac{Q' - (Q_{rxn} - Q_r - Q_{sh})}{(Q_{rxn} - Q_r - Q_{sh})} \right| < 1\% \quad (18)$$

in which Q' is calculated as follows:

$$Q' = \Delta h_{c1} + \Delta h_{c2} + \Delta h_{a1} + \Delta h_{a2} \quad (19)$$

Where:

Δh_{c1} , Δh_{a1} are the enthalpy changes of reactants at the cathode and anode sides, respectively; and Δh_{c2} and Δh_{a2} are the enthalpy changes of products at the cathode and anode sides, respectively [3].

Performance of SOFC: Power fuel cell parameters were calculated as following [4]:

$$I = 2Fz \quad (20)$$

$$I = iA \quad (21)$$

$$\dot{W}_{dc,SOFC} = EI \quad (22)$$

Where:

A, i and F are cell area, current density and Faraday constant, respectively.

Therefore, entropy generation rate of SOFC can be calculated as:

$$\dot{S}_{gen,SOFC} = \dot{n}_6 s_6 - \dot{n}_3 s_3 - \dot{n}_5 s_5 \quad (23)$$

Combustion Chamber: Applying energy balance to the adiabatic combustion chamber and using of combustor efficiency, flame temperature is obtained. Therefore, entropy generation rate of CC can be calculated as:

$$\dot{S}_{gen,CC} = \dot{n}_7 s_7 - \dot{n}_5 s_5 - \dot{n}_6 s_6 \quad (24)$$

Gas Turbine: Power input to the air and fuel compressors are supplied by the gas turbine.

$$\eta_{mech,GT} \dot{W}_{GT} = \dot{W}_{ac} + \dot{W}_{fc} \quad (25)$$

Where:

$\eta_{mech,GT}$ is GT mechanical efficiency. Entropy generation rate of GT is calculated as following [18].

$$\dot{S}_{gen,GT} = \dot{n}_7 (s_7' - s_7) \quad (26)$$

Power Turbine: Isentropic efficiency of power turbine is calculated as:

$$\eta_{PT} = \frac{W_{PTa}}{W_{PTs}} = \frac{h_{7'} - h_8}{h_{7'} - h_{8s}} \quad (27)$$

$$\frac{T_{8s}}{T_{7'}} = \left(\frac{P_8}{P_{7'}} \right)^{\frac{K_{7'}}{K_{7'} - 1}} \quad (28)$$

$$\text{that } K_{7'} = \frac{C_{p7'}}{C_{v7'}}$$

$$\dot{W}_{PT} = \dot{n}_{7'} (h_{7'} - h_8) \quad (29)$$

Therefore entropy generation rate of GT can be calculated as follows:

$$\dot{S}_{gen,PT} = \dot{n}_{7'} (s_8 - s_{7'}) \quad (30)$$

Overall System: Total thermal efficiency of the SOFC/GT hybrid system is defined as the ratio of net output work to the total rate of energy input to the system [18]:

$$\eta_{th}^{cyc} = \frac{\dot{W}_{net}}{\dot{Q}_{tot}} \quad (31)$$

$$\dot{W}_{net} = \dot{W}_{ac,sofc} + \dot{W}_{Gen} \quad (32)$$

$$\dot{W}_{ac,IRSOFC} = \eta_{inver} \dot{W}_{dc,IRSOFC} \quad (33)$$

$$\dot{W}_{Gen} = \eta_{Gen} \dot{W}_{PT} \quad (34)$$

$$\dot{Q}_{tot} = \dot{n}_{fuel} LHV_{fuel} = \dot{n}_4 LHV_{ng} \quad (35)$$

The total entropy generation rate of GT can be calculated as:

$$\dot{S}_{gen,tot} = \dot{S}_{gen,fc} + \dot{S}_{gen,ac} + \dot{S}_{gen,CC} + \dot{S}_{gen,PT} + \dot{S}_{gen,GT} + \dot{S}_{gen,SOFC} \quad (36)$$

RESULTS AND DESCUSSION

To perform the calculations, the values of Table 1 are utilized. Also the following assumptions were made:

- Heat losses from all the system components are negligible.
- All gases act as ideal-gases.
- Cathode outlet temperature is the same as the anode one.
- Steady state flow is established in all the system components.

In this study, the pressure ratio, the inlet temperature and the inlet pressure of both compressors were set to 9, 300K and one bar, respectively. The air flow rate, the fuel flow rate and the fuel utilization rate were set to 170 kmol /hr, 15 kmol /hr and 0.8, respectively. The total number of tubular SOFCs used in all cases was set to 60 000. Table 2 shows the results.

Effect of Fuel Flow Rate on the System Performance:

The effect of fuel flow rate on the SOFC power, PT power output, system efficiency, total entropy generation rate and CO₂ emission is shown in Figs. 2 to 5. In this case study, the pressure ratios of the fuel and air compressors were set at 9, the air flow-rate at 170 kmol/h and fuel utilization at 0.8. At a constant fuel utilization, a higher rate of fuel flow means that more chemical energy is converted to electrical energy. Accordingly, more current will be produced; hence the current density is increased. This increase in current density has a linear relationship with the amount of hydrogen consumed.

Table 1: Data for analysis of SOFC/GT hybrid system

parameter	Assumed value
Cell pressure drop	2%
Combustor efficiency	95%
Cell area (A)	270 cm ²
Cell length	50
Generator efficiency (η_{gen})	97%
Inverter efficiency (η_{inv})	96.5%
Power turbine isentropic efficiency (η_{PT})	85%
Gas turbine mechanical efficiency (η_{mech})	99%
Recuperator pressure drop	0.13 bar
Recuperator effectiveness	0.92
Compressor isothermal efficiency ($\eta_{isoth,ac}$, $\eta_{isoth,fc}$)	85%

Table 2: Output results for the SOFC/GT hybrid system

Performance parameters	Predicted values
System net power (kW)	9800
System thermal efficiency (%)	61.06
Power ratio	1.77
Cell voltage (V)	0.57
Cell current density (mA/cm ²)	318
Air utilization factor	0.16
SOFC stack temperature (K)	1121
M _{CH4,tot} (kg/s)	0.32

Naturally, an increase in fuel flow rate causes an increase in current and thus raises the power output of the fuel cell stack. Increase in stack temperature and gas flow rate brings about increase in turbine power output, as indicated in Fig. 2.

The more the fuel enters the reaction, the more total entropy generation rate increases, as indicated in Fig. 3. As it is seen, total entropy generation rate for the GT system is generally higher than that of the SOFC/GT system.

The system efficiency decreases with increasing the fuel flow rate, as shown in Fig. 4. Increase in fuel consumption leads in a decline in the system efficiency, though stack and turbine power outputs have increased. The CO₂ emission increases as fuel consumption increases, as is shown in Fig. 5. As it is seen, the first law efficiency of the GT system is generally lower and its CO₂ emission is higher than the SOFC/GT system.

Effect of Compressors Pressure Ratio on the System Performance:

Effect of pressure ratio of compressors on the SOFC power, PT power outputs, system efficiency, total entropy generation rate and CO₂ emission is shown in Figs. 6 to 9. For this case study, the fuel flow-rate was

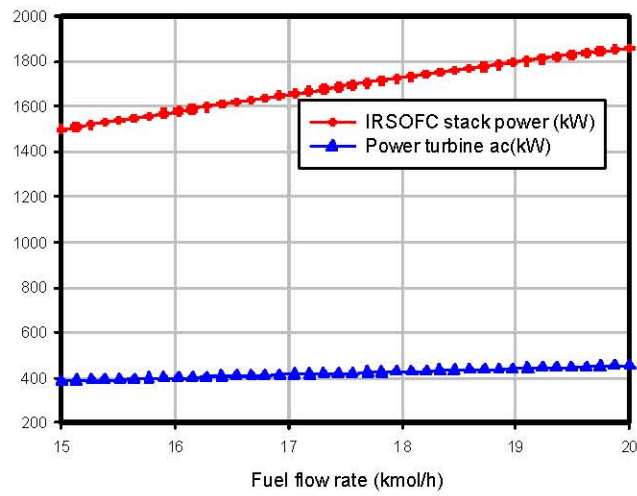


Fig. 2: Effect of fuel flow rate on SOFC stack power and power turbine

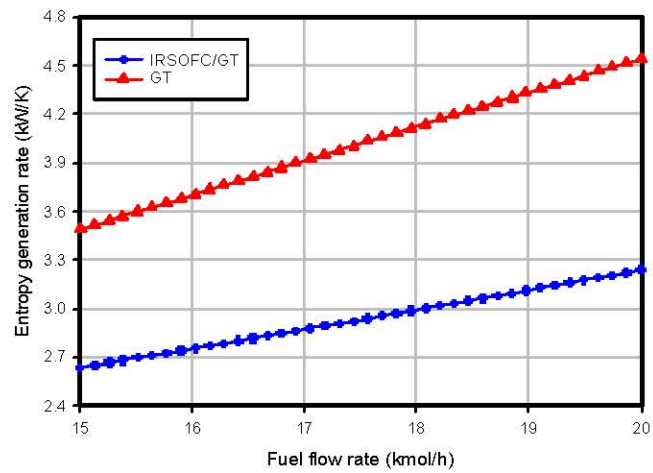


Fig. 3: Effect of fuel flow rate on entropy generation rate

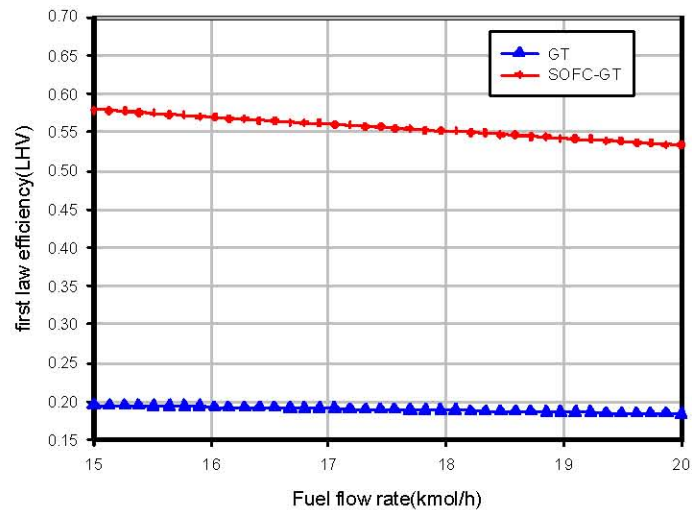


Fig. 4: Effect of fuel flow rate on first law efficiency

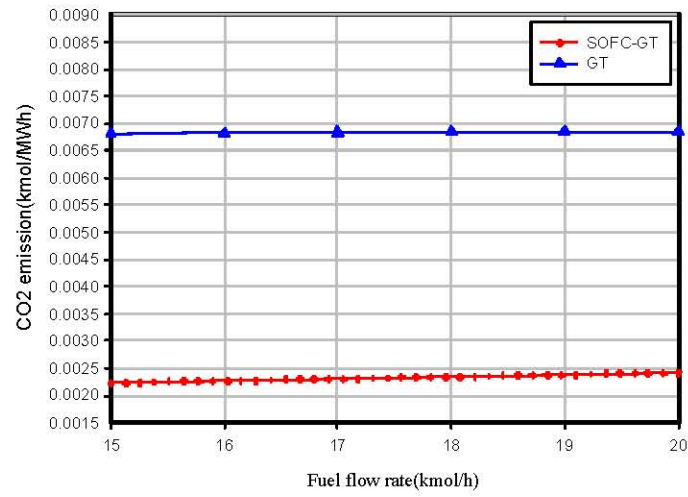


Fig. 5: Effect of fuel flow rate on CO₂ emission

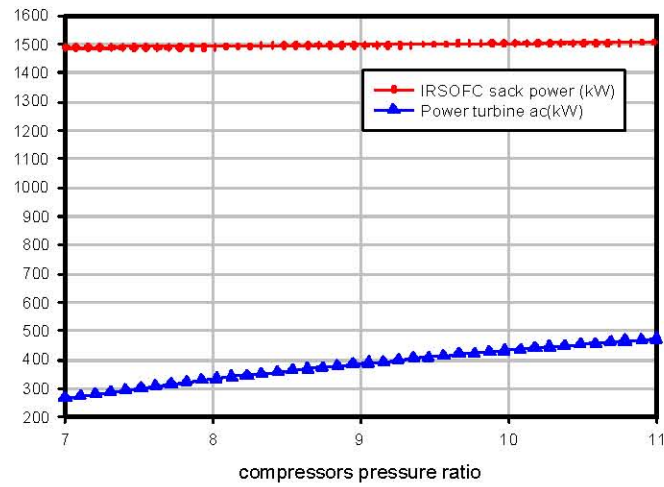


Fig. 6: Effect of compressors pressure ratio on SOFC stack power and power turbine

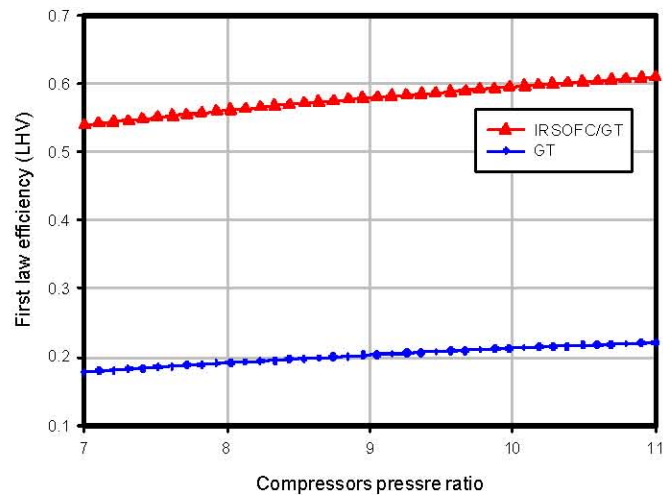


Fig. 7: Effect of compressors pressure ratio on first law efficiency

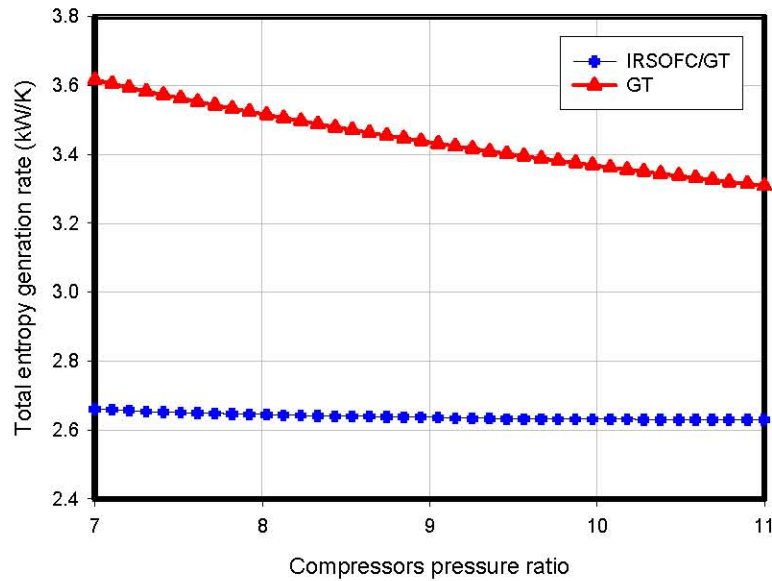


Fig. 8: Effect of compressors pressure ratio on total entropy generation rate

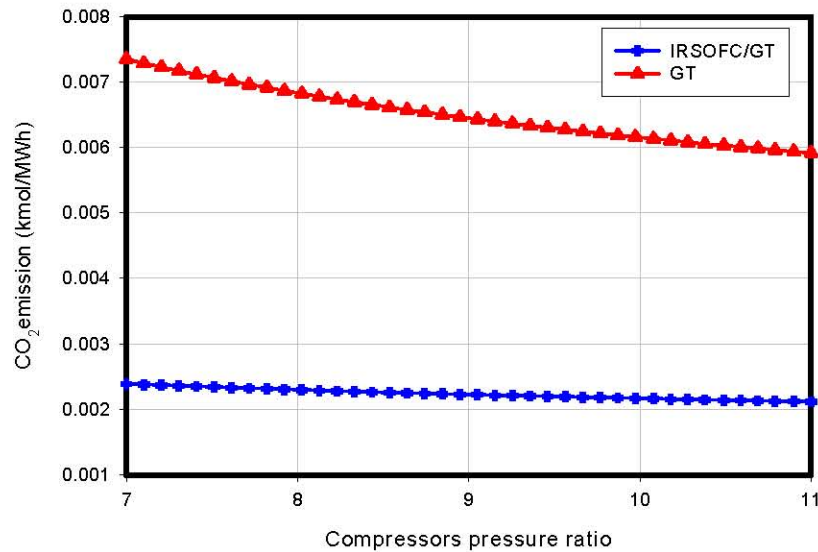


Fig. 9: Effect of compressors pressure ratio on CO₂ emission

set at 15 kmol h⁻¹, the air flow-rate at 170 kmol h⁻¹ and fuel utilization at 0.8. With an increase in cell pressure, temperature of cell raises therefore more heat and power is produced. Increase in temperature and pressure at the exhaust of SOFC increases the capabilities of both GT and PT for power production. This effect is shown in Fig. 6.

Since the overall power of the system has increased at a constant fuel flow rate, the first law efficiency has been improved, as is shown in Fig. 7. As it is seen the first

law efficiency of the GT system is generally lower than that of the SOFC/GT system. Finally as shown in Figs. 8 and 9, the total entropy generation rate and CO₂ emission of the system decrease with increase in pressure of the system. Also both the total entropy generation rate and CO₂ emission for the GT system are generally higher than those of the SOFC/GT system. Hence results indicate that this hybrid system is very promising from both air pollution and energy saving points of view.

CONCLUSION

The effect of different parameters upon SOFC/GT hybrid system was studied. The results of this investigation can be summarized as following:

- Increase in compressor pressure ratio would have positive impact on the system efficiency and net power output of the system.
- At fixed fuel utilization, the effect of fuel flow-rate on the system efficiency is not significant.
- For the proposed hybrid system, the first law efficiency approaches 60%, whereas its entropy generation rate is less than that of the gas turbine.
- Results indicate that this hybrid system is very promising from both air pollution and energy saving points of view.

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