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THERMODYNAMIC ANALYSIS OF AN INTERNAL REFORMING SOLID-OXIDE FUEL CELL COMBINED WITH A 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 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 CO_2 emission. The results revealed that it is possible for this system to reach a first law efficiency of about 60% and optimum entropy generation rate at that of gas turbine.

NOMENCLATURE

E	[V]	Cell potential
F	[96 487 C/mol]	Faraday constant
h	[kJ/kmol]	Enthalpy
i	[mA/cm^2]	Current density
n_i	[kmol/h]	Molar flow rate
P	[bar]	Pressure
Q	[kW]	Heat transfer rate
R	[8.314 kJ/kmol K]	Universal gas constant
s	[kJ/kmol K]	Entropy
T	[K]	Temperature
U_f	[-]	Fuel utilisation
Subscripts		
a		anode
c		cathode
r		reforming reaction
sh		shifting reaction
re		reversible

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. Calise et al. [9-12], Granovskii et al. [15], Ghanbari [16], Haseli et al. [17], and Motahar and Alemrajabi [18] investigated SOFC/GT hybrid systems by exergy. Haseli et al. [19] investigated SOFC/GT hybrid systems by entropy analysis.

In the present work a SOFC/GT hybrid system is simulated and analyzed and the cycle performance including entropy generation rate and CO_2 emission is investigated. Also a parametric study was 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 CO_2 emission.

SYSTEM DESCRIPTION:

Layout of an internal reforming solid oxide fuel cell and gas turbine (IRSOFC/GT) hybrid system with recuperator which is considered in this study is shown in Fig. 1.

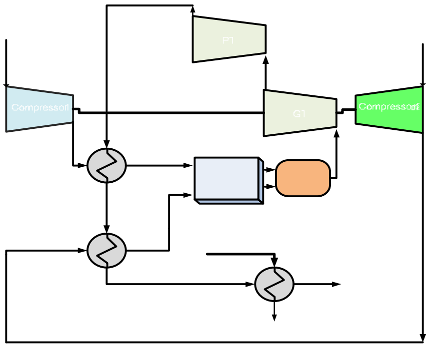

Figure 1 layout of IRSOFC/GT hybrid system with recuperated.

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 IRSOFC/GT hybrid system is composed of an IRSOFC stack, a combustor chamber, a GT and a power turbine (PT), a fuel compressor (FC), an air compressor (AC), and three recuperators.

Ambient air at point 1 is entered to the cycle and compressed by the AC up to point 2. Then the air is preheated in the recuperator 1 (RE1) and passed to the cathode inlet of the IRSOFC stack at point 3. Similarly, the fuel at point 4 is entered and compressed by the FC up to point 5, preheated in the recuperator 2 (RE2) and then passed to the anode inlet of the IRSOFC stack at point 6. In the IRSOFC 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]. Anode and cathode outlet streams from IRSOFC stack, i.e. air and fuel at points 7 and 8 react in the combustion chamber. Combustion products at point 9 are entered into the gas turbine and produce mechanical work. This mechanical work is used to drive the AC and FC. The outlet stream from the GT at point 10 enters the PT and its outlet stream is fed into the three recuperators. Similar to a conventional combined heat and power (CHP) system, recuperator 3 (RE3) is utilized for water heating.

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 (AC):

The isothermal efficiency of air compressor is defined as:

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

Where T_1 is the inlet temperature of AC and r_p is the pressure ratio of the compressors. One can Use this equation to calculate the actual outlet temperature of AC.

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

$$\dot{Q}_{surr,ac} = n_1(s_2 - s_1).[\frac{T_1 + T_2}{2}] \tag{2}$$

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

Similar calculations may be done for the fuel compressor (FC).

-RECUPERATOR (RE):

Using the ε-NTU method, calculation of heat transfer between clod and hot fluids can be performed for counter flow recuperator, RE_1. The effectiveness of RE is defined as:

$$\varepsilon_{\mathrm{Re}c1} = \frac{T_3 - T_2}{T_{11} - T_2} \tag{4}$$

And energy balance for RE_1 may be written as:

$$\dot{n}_2(h_3 - h_2) = \dot{n}_{11}(h_{11} - h_{12}) \tag{5}$$

Therefore entropy generation rate can be calculated as:

$$\dot{S}_{gen,\mathrm{Rec}1} = \dot{n}_2(s_3 - s_2) - \dot{n}_{11}(s_{11} - s_{12}) \tag{6}$$

Other recuperators are analysed in the same manner as the first recuperator.

-INTERNAL REFORMING SOLID OXIDE FUEL CELL (IRSOFC):

The IRSOFC 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 Ref. [20].

-CHEMICAL REACTIONS IN AN INTERNAL REFORMING:

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

$$x = CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (\mathrm{Reforming}) \tag{7}$$

$$y = CO + H_2O \leftrightarrow CO_2 + H_2 \quad (Shifting) \tag{8}$$

$$z = H_2 + 1/2O_2 \to H_2O \quad (Electrochemical) \tag{9}$$

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:

$$LogKp = AT^4 + BT^3 + CT^2 + DT + E \tag{10}$$

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

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

$$Kpr = \frac{\left(\left([CO]^i + x - y\right)\left([H_2]^i + 3x + y - z\right)^3\right)}{\left(\left([CH_4]^i - x\right)\left([H_2O]^i - x - y - z\right)\right)\left(n^i{}_t + 2x\right)^2} P^2{}_{cell} \tag{11}$$

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

$$Z = U_f(3x + y) \tag{13}$$

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:

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

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

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

$$Q = Q_{rxn} - Q_r - Q_{sh} \tag{16}$$

-POTENTIAL OF IRSOFC:

The actual potential of a fuel cell would be:

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

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 and are calculated easily [3].

-TEMPERATURE OF IRSOFC:

By writing energy balance on the control volume of IRSOFC, the temperature of IRSOFC can be calculated by an iterative computational method [3]:

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

In which Q' is calculated as follows:

$$Q' = \Delta h_{c1} + \Delta h_{c2} + \Delta h_{a1} + \Delta h_{a2} \tag{19}$$

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 IRSOFC:

Power fuel cell parameters were calculated as follows:

$$i = 2Fz \tag{20}$$

$$I = iA \tag{21}$$

$$\dot{W}_{dc,IRSOFC} = EI \tag{22}$$

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

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

$$\dot{S}_{gen,IRSOFC} = \dot{n}_7 s_7 - \dot{n}_8 s_8 - \dot{n}_3 s_3 - \dot{n}_6 s_6 \tag{23}$$

-COMBUSTION CHAMBER (CC):

By applying the energy balance to the adiabatic combustion chamber, and use of combustor efficiency, flame temperature was obtained. Therefore entropy generation rate of CC can be calculated as follows:

$$\dot{S}_{gen,CC} = \dot{n}_9 s_9 - \dot{n}_7 s_7 - \dot{n}_8 s_8 \tag{24}$$

-GAS TURBINE (GT):

Power input to the air and fuel compressors were supplied by the gas turbine.

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

Where $\eta_{mech,GT}$ is GT mechanical efficiency. Entropy generation rate of GT was calculated as follows:

$$\dot{S}_{gen,GT} = \dot{n}_9(s_{10} - s_9) \tag{26}$$

-POWER TURBINE (PT):

Specific isentropic efficiency of power turbine were Calculated as follows:

$$\eta_{PT} = \frac{W_{PTa}}{W_{PTs}} = \frac{h_{10} - h_{11}}{h_{10} - h_{11s}} \tag{27}$$

$$\frac{T_{11\,s}}{T_{10}} = \left(\frac{P_{11}}{P_{10}}\right)^{\frac{K_{10}}{K_{10}-1}} \tag{28}$$

$$that \quad K_{10} = \frac{C_{p10}}{C_{v10}}$$

$$\dot{W}_{PT} = \dot{n}_{10}(h_{10} - h_{11}) \tag{29}$$

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

$$\dot{S}_{gen,PT} = \dot{n}_{10}(s_{11} - s_{10}) \tag{30}$$

-OVERALL SYSTEM:

Total thermal efficiency of the IRSOFC/GT hybrid system was defined as the ratio of net output work to the total rate of energy input to the system:

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

$$\dot{W}_{net} = \dot{W}_{ac,sofc} + \dot{W}_{Gen} \tag{32}$$

$$\dot{W}_{ac,IRSOFC} = \eta_{invert}\dot{W}_{dc,IRSOFC} \tag{33}$$

$$\dot{W}_{Gen} = \eta_{Gen}\dot{W}_{PT} \tag{34}$$

$$\dot{Q}_{tot} = \dot{n}_{fuel}LHV_{fuel} \tag{35}$$

$$= \dot{n}_4 LHV_{ng}$$

Hence the total entropy generation rate of GT can be calculated as follows:

$$\dot{S}_{gen,tot} = \dot{S}_{gen,fc} + \dot{S}_{gen,ac} + \dot{S}_{gan,CC} + \dot{S}_{gen,PT} \tag{36}$$

$$+ \dot{S}_{gen,GT} + \dot{S}_{gen,IRSOFC}$$

RESULTS AND DISCUSSION:

To perform the calculations, values were assigned to the parameters of the described system. Table (1) describes such values:

Table 1 data for analysis of IRSOFC/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%
Invertor efficiency (η_{inv})	96.5%
Power turbine isentropic efficiency (η_{PT})	85%
Gas turbine mechanical efficiency (η_{mech})	99%
Recuperator pressure drop	1%
Recuperator effectiveness	0.8
Compressor isothermal efficiency ($\eta_{isoth,ac}$, $\eta_{isoth,fc}$)	85%

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 case 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 IRSOFCs used in all cases was set to 60 000. Table (2) shows the results:

Table 2 output results for the IRSOFC/GT hybrid system

Cell voltage	0.7179 V
Current density	137.5 mA/cm2
Exhaust temperature	399 K
Cell temperature	1165 K
AC work	307 kW
FC work	26.8 kW
Power turbine (ac)	387.8 kW
Fist law efficiency	59.54%
Second law efficiency	57.4%
Total entropy generation rate	2.7 kW/K

-EFFECT OF FUEL FLOW RATE ON THE SYSTEM PERFORMANCE:

The effect of fuel flow rate on the IRSOFC power, PT power output, system efficiency, total entropy generation rate and CO_2 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^{-1} 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. 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 IRSOFC/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 CO_2 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 CO_2 emission is higher than the IRSOFC/GT system.

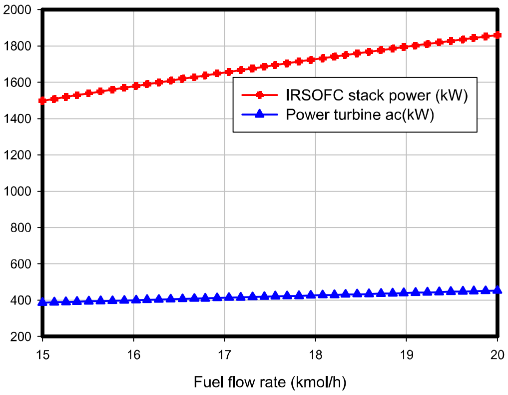

Figure 2 Effect of fuel flow rate on IRSOFC stack power and power turbine

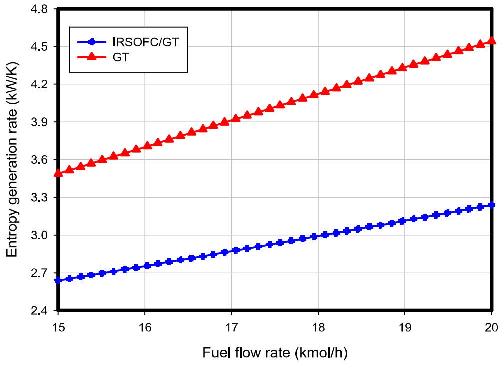

Figure 3 Effect of fuel flow rate on entropy generation rate

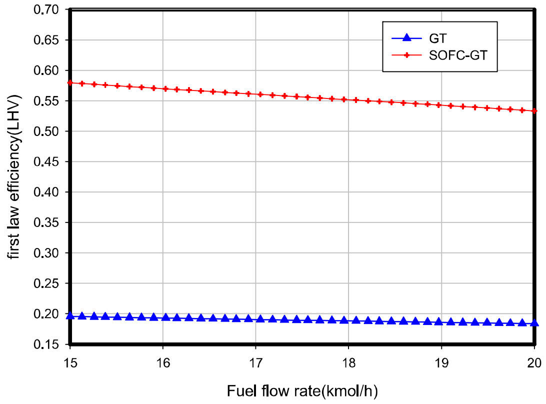

Figure 4 Effect of fuel flow rate on first law efficiency.

- EFFECT OF COMPRESSORS PRESSURE RATIO ON THE SYSTEM PERFORMANCE:

Effect of pressure ratio of compressors on the IRSOFC power, PT power outputs, system efficiency, total entropy generation rate and CO_2 emission is shown in Figs. 6 to 9. For this case study, the fuel flow-rate was 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 IRSOFC increases the capabilities of both GT and PT for power production. This effect is shown in Fig. 6.

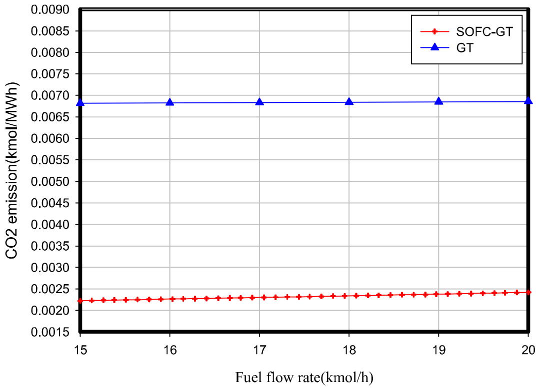

Figure 5 Effect of fuel flow rate on CO_2 emission

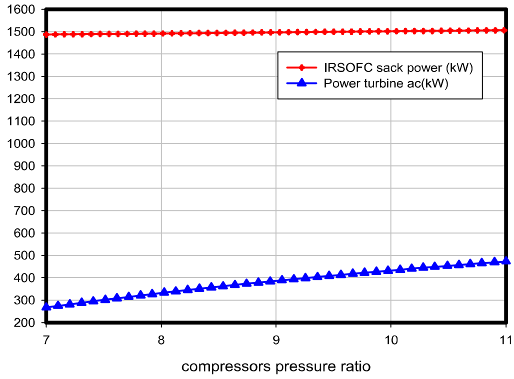

Figure 6 Effect of compressors pressure ratio on IRSOFC stack power and power turbine

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 IRSOFC/GT system. Finally as shown in Figs. 8 and 9, the total entropy generation rate and CO_2 emission of the system decrease with increase in pressure of the system. Also both the total entropy generation rate and CO_2 emission for the GT system are generally higher than those of the IRSOFC/GT system. Hence results indicate that this hybrid system is very promising from both air pollution and energy saving points of view.

CONCLUSIONS:

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

1-Increase in compressor pressure ratio would have positive impact on the system efficiency and net power output of the system.

2-at fixed fuel utilization, the effect of fuel flow-rate on the system efficiency is not significant.

3- For the proposed hybrid system, the first law efficiency approaches 60%, whereas its entropy generation rate is less than that of the gas turbine.

4- Results indicate that this hybrid system is very promising from both air pollution and energy saving points of view.

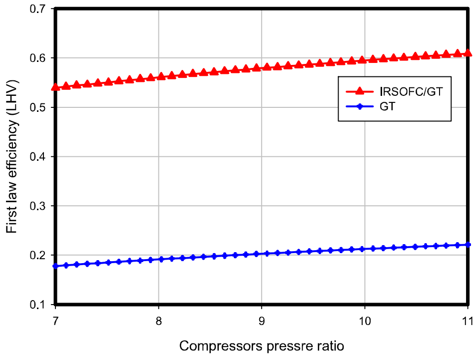

Figure 7 Effect of compressors pressure ratio on first law efficiency

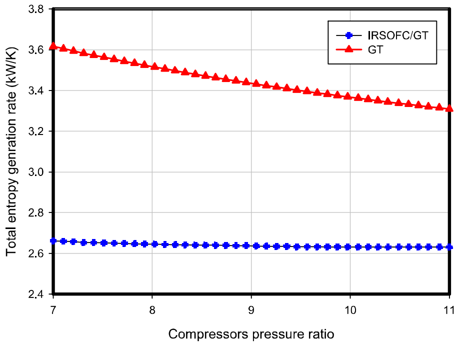

Figure 8 Effect of compressors pressure ratio on total entropy generation rate

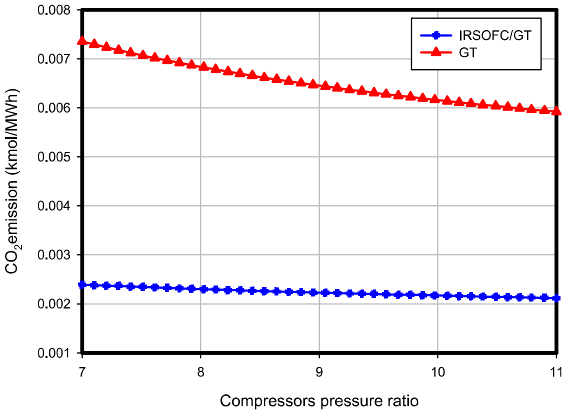

Figure 9 Effect of compressors pressure ratio on CO_2 emission

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