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THERMODYNAMICS ANALYZES OF THE HYBRID GAS TURBINE-SOLID OXIDE FUEL CELL SYSTEMS (GT-SOFC)

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Abstract. *This study examines the performance of a high-temperature solid oxide fuel cell combined with a conventional recuperative gas turbine (GT–SOFC) plant, as well as the irreversibility within the system. Individual models are developed for each component, through applications of the first, second laws of thermodynamics and exergetic analyses. The overall system performance is then analyzed by employing individual models and further applying thermodynamic laws for the entire cycle, to evaluate the thermal efficiency, entropy production, exergy efficiency and, exergy destruction of the plant. The results of an assessment of the cycle for certain operating conditions are compared against those available in the literature. The comparisons provide useful verification of the thermodynamic simulations in the present work. The main parameters analyzed were the compression ratio (rp) and the turbine inlet temperature (TIT). A comparison between the GT–SOFC plant and a traditional GT cycle, based on identical operating conditions, is also made, showing an increase of power in order of 71%. .*

Keywords: *Fuel cell, gas turbine, hybrid cycle, exergetic analysis*

1. INTRODUCTION

The increase in consumption of energy leads to a scenario of uncertainties with regard to the guarantee in the supply of energy, due to this aspect are necessary new alternative sources of power generation. In accordance with the website of the Energia (2009) (Ministry of Mines and Energy) is currently generated by 13257MW thermoelectric plants existing until early 2008. Second Tavares (1999) one of the alternatives for the production of electrical energy would be through natural gas, encouraged by factors such as the price and the pollution, remembering that the environmental impacts resulting from the burning of natural gas are less intense than the burning of fuel oil. The supply of natural gas will be much greater than the expected increase of thermoelectric power plants and the increase in the use of fuel gas in the industrial area due to the migration of the majority of the equipment, such as for example, furnaces and boilers, solid fuel to natural gas. The principle, the use of natural gas in thermal installations can be performed by means of any technology: turbine, the gas piston engines, burning in boilers, etc. In this way, power generation systems more efficient and less pollution are necessary. In this study was used models zero-dimensional also called black-box for the simulation of solid oxide fuel cell by more simplified and more suitable for the analysis of hybrid cycle GT-SOFC (Gas Turbine –Solid Oxide Fuel Cell). In this way, models thermodynamic for each component of the hybrid system, such as for example; compressor, heat exchanger , heat, turbine, reformer and of the fuel cell itself among others were simulated according to the classic books of thermodynamics, for example Çengel and Boles (2006).

2. SOLID OXIDE FUEL CELL

According to EG&G Technical Services (2004), the operation of fuel cells is identical for all types of cells and to a conventional galvanic cell (conventional batteries), i.e. the anode, a fuel is oxidized giving rise to electrons and protons, and in the cathode, the oxygen is reduced, forming a sort of oxide, i.e., they represent a new conception of electricity generation from the direct conversion of chemical energy of a fuel into electricity. So there is a potential difference in electrochemical reactions that generate an electrical current between anode and cathode, closing an electrical circuit and at the same time there is also a flow of ions through a middle driver, called electrolyte. Thus, the fuel cells consist basically of two electrodes, one positive and the other negative, designated by cathode and anode, respectively and an electrolyte which has the function of transporting ions produced on the anode to cathode contrary.

In general, the choice of electrolyte determines the limit of the operating temperature of the cell and its useful life. It is the electrolyte also that defines the type of fuel cell, because it is the heart of the chemical reaction and the production of electrical energy. Therefore, as shown in Tab. 1, the fuel cells can be classified according to its electrolyte, and from it has also the other specifications of its basic components, such as, for example, the type of fuel, the operating temperature, among others.

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Table 1. Types of fuel cell.

	PEMFC Membrane Proton Exchanger Fuel Cell	AFC Alkaline Fuel Cell	LRP Phosphoric Acid Fuel Cell	MCFC Molten Carbonate Fuel Cell	SOFC Solid Oxide Fuel Cell
Electrolyte	Membrane ion exchange polymer	Potassium hydroxide	Phosphoric acid liquid in SiC	Molten Carbonate liquid in $LiAlO_2$	Ceramics
Electrodes	Carbon	Transition Metals	Carbon	Nickel and Nickel oxide	Metal
Catalytic Converter	Platinum	Platinum	Platinum	Electrode Material	Electrode Material
Operating Temperature	40 - 80°C	65 - 220°C	205°C	605°C	600 - 1000 °C
Efficiency (%)	45	50	45	50	50
Power (kW)	1-1000	10-100	100-5000	100-10000	1000-100000
Applications	Portable and transport	Spaceships	Stationary	Stationary	Stationary

In this way, as the objective of the present work and the combined cycle GT-SOFC, the focus of the work and the fuel gas methane and the cell type of SOFC (Solid Oxide Fuel Cell), which are cell the fuel they use electrolyte based solid of Yttrium-Zirconium. The SOFC have an operating temperature extremely high between 600ºC and 1000°C for which the ceramic materials are preferably used as catalysts in the electrodes, thus precluding the use of noble metals and favoring the co-generation thermoelectric where they deliver high energy efficiency in cases of combined cycles.

The solid oxide fuel cells are divided into two types of geometries: the tubular and flat. The tubular geometry and most used due to its greater simplicity of seal, the remaining types of fuel cell as for example the polymeric membrane, are most often used in vehicles, and prefer the geometry flat. The electrolyte is the most important part that ensures the flow of oxygen ions from the cathode to the anode. The material most often used in the electrolyte of SOFC is zirconium (ZrO_2) stabilized as yttrium (Y_2O_3), which receives the name YSZ.

As the hydrogen and the main reaction reagent electrochemistry arrives to one of the most important disadvantages of the technology of fuel cells, because on earth there is no hydrogen free; and to be obtained "pure hydrogen" is necessary to consume energy on the decoupling of a primary source. Currently almost 96% of the world production of hydrogen derived from the use of fossil fuels, being the natural gas the most employed, therefore, the choice of methane and in Brazil has been very used the hydrocarbon ethanol is a fuel of renewable origin. For obtaining the hydrogen the SOFC has a great advantage over the other types because due to its high temperature she makes the reform of hydrocarbon directly within the cell. The system of fuel cell hybrid and the combination of conventional thermal machines (e.g. , gas turbines, steam turbines, among others) with different types of fuel cell or combination of the two types, being the system, suitable for the stationary applications (centralized or distributed). The ability to use both gas turbines and/or steam turbines in a combined cycle with a SOFC was for many years known in concept, however, only recently after the fuel cell began to operate pressurized and that the cycles combined had a better performance in the combination of hybrid cycles, called GT-SOFT, when combined with a gas turbine and becoming then a technology more viable and attractive. The Siemens Westinghouse, with the project SureCellTM, produced the first concept of GT-SOFT combined commercial for the plant to 300kW. (Siemens, 2007).

An important aspect of the review of the literature revealed that only a few works have studied the irreversibility combined cycle GT-SOFT by applying the second law of thermodynamics, among which stand out the from: : George (2000), Costamagna et al. (2004), Chan et al. (2003a), Calise et al. (2006). Haseli et al. (2008) which presents an analysis exegetic in order to find the thermodynamic losses of each component and to evaluate the potential of work of different flows and interactions of heat. In the Tab. 2 are presented some work on GT-SOFC.

The hybrid system GT-SOFT has a very interesting future for distributed generation, mainly for the industrial sector that cannot suffer lack of energy due to the transmission of network. Thus the advantages of this system are beyond in value and in many respects the conventional system. In this way, such aspects have to demand of cycles of hybrids in the industrial sector increased considerably in the last few decades because mainly of the concerns with the environment, emissions of CO_2 and the demand for security of supply of energy with the generation distributed The

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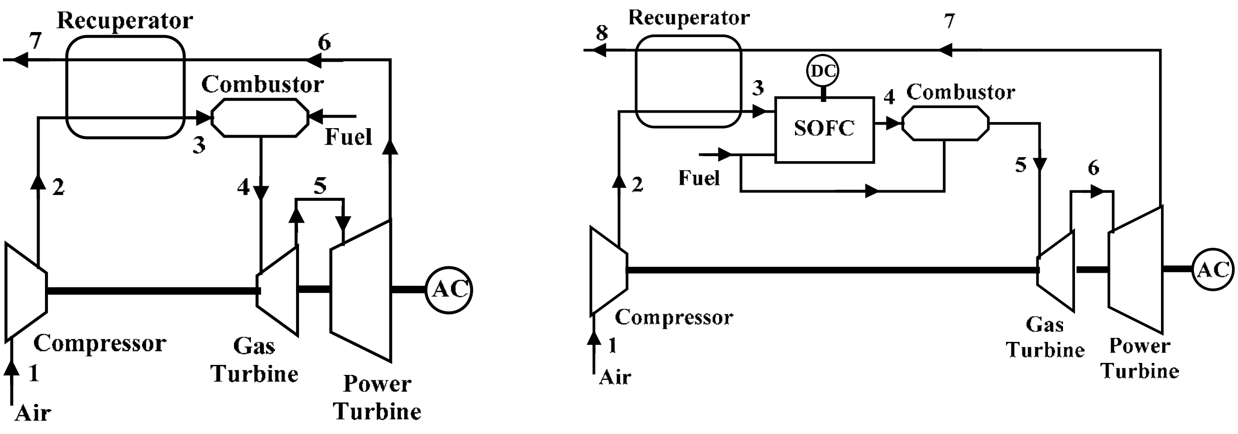
systems GT-SOFT can thus contribute in many ways to increase the thermal efficiency of power generation systems within the manufacturing plant that before this new vision of better performance and utilization wasted part of the energy consumed in various forms of heat.

Table 2. Summary of some hybrid systems and efficiencies. (Haseli et al., 2008)

Reference	Efficiency
Harvey and Ricther (1994)	68.1
George (1997)	60-65
Campanari and Macchi (1998)	70<
Costamagna et al. (2001)	60<
Chan et al. (2002)	60<
Rao and Samuelsen (2003)	66.23
Rao and Samuelsen (2003)	75.68
Chan et al. (2003b)	60<
Calise et al. (2006)	60
Araki et al. (2007)	68.5
Tse et al. (2007)	59.4
Tse et al. (2007)	68.7
Haseli et al. (2008)	60.6

3. GAS TURBINE-SOLID OXIDE FUEL CELL MATHEMATICAL MODEL

Initially, the simulation was applied to the Brayton regenerative cycle, Fig. 1(a), in order to provide in addition to a comparative analysis as the results of the simulation of GT-SOFC hybrid cycle, Fig 1(b), the validation of the mathematical model.



(a) Brayton regenerative cycle

(b) GT-SOFC hybrid cycle

Figure 1. Diagram of the cycles with each point analyzed

The model zero-dimensional also called "black box" was chosen for the analysis of GT-SOFT hybrid cycle. Thus, thermodynamic models, i.e. models that use the equations of conservation of mass, the first law of thermodynamics, the second law of thermodynamics and exergetic for each component were simulated through the entry of all equations and parameters of operation of the hybrid system GT-SOFC in software EES (Engineering Equation Solver), developed by Klein and Alvarado (1995) and obtained the results according to the reference bibliographic of studies obtained by Haseli et al. (2008), Haseli et al. (2008) and Tse et al. (2007). Following was summarized the main equations of each component Tab. 3.

Table 3. Summary of equations for each component.

Component	Efficient	Power	Exergy Destruction	Efficient II
Compressor	$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1}$	$\dot{W}_C = \dot{m}_1 (h_2 - h_1)$	$Ex_{dest,C} = T_o S_{gen,C}$	$\eta_{II,C} = \frac{\dot{m}_3 (ex_2 - ex_1)}{\dot{W}_C}$
Recuperator	$\varepsilon_{recup} = \frac{T_3 - T_2}{T_7 - T_2}$	$\dot{m}_2 (h_3 - h_2) = \dot{m}_7 (h_7 - h_8)$	$Ex_{dest,Recup} = T_o S_{gen,Recup}$	$\eta_{II,Recup} = \frac{\dot{m}_3 (ex_3 - ex_2)}{\dot{m}_7 (ex_7 - ex_8)}$
Gas Turbine	$\eta_{TG} = \frac{h_5 - h_6}{h_5 - h_{6s}}$	$\dot{W}_{TG} = \dot{W}_C$	$Ex_{dest,TG} = T_o S_{gen,TG}$	$\eta_{II,TG} = \frac{\dot{m}_5 (h_5 - h_6)}{\dot{m}_5 (ex_5 - ex_6)}$
Power Turbine	$\eta_{TP} = \frac{h_6 - h_7}{h_6 - h_{7s}}$	$\dot{W}_{TP} = \dot{m}_6 (h_6 - h_7)$	$Ex_{dest,TP} = T_o S_{gen,TP}$	$\eta_{II,TP} = \frac{\dot{W}_{TP}}{\dot{m}_5 (ex_6 - ex_7)}$

In this way, and presented the following analysis more depth of the equations that govern the functioning of the cell and the combustor due such components play an important role in the performance of the cycle and in the generation of entropies with this in irreversibility thus beginning by Eq. (1) that shows the reagents and the products of the reaction of electrochemical cell SOFC that uses this case specific fuel methane.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

The Eq. (2) is the fundamental equation for the calculation of the work of the fuel cell, called Nernst equation that uses the partial pressures of each reagent and product of electrochemical reaction with the aim of calculating the potential of the cell, this potential and done the calculation of cell voltage V_{cell} according to Eq. (3) where the losses by activation, ohmic and concentration are calculate, Eq. (4).

$$E = E_o + \frac{RT}{8F} ln \left[\frac{P_{CH_4} P_{O_2}^2}{P_{CO_2} P_{H_2O}^2} \right] \tag{2}$$

$$V_{cell} = E - \Delta V_{losses} \tag{3}$$

$$\Delta V_{losses} = V_{activation} + V_{ohmic} + V_{concentration} \tag{4}$$

For calculation of the work of the cell Eq. (5) is also required operating parameters of the SOFC, as density j and the area of each cell A_{cell}. After the calculation of the work is done the balance of energy, entropy and consumption for the calculation of efficient and exergy destroyed this component, in accordance with the Eq. (6) to (8)

$$\dot{W}_{cell,DC} = V_{cell}\, j\, A_{cell}\, N_{stack} \tag{5}$$

$$\dot{m}_3 h_3 + \dot{m}_{fuel,cell} UF_{fuel} LHV + \dot{m}_{fuel,cell} \left(1 - UF_{fuel}\right) h_{fuel} = \dot{W}_{cell,DC} + \dot{m}_4 h_4 \tag{6}$$

$$Ex_{dest,cell} = \dot{m}_3 ex_3 + \dot{m}_{fuel,cell} ex_{physical} + \dot{m}_{fuel,cell} UF_{fuel} ex_{chemical} - \dot{m}_4 ex_4 - \dot{W}_{cell,DC} \tag{7}$$

$$\eta_{II,cell} = \frac{\dot{W}_{cell,DC}}{(\dot{m}_{fuel,cell} ex_{physical} + \dot{m}_{fuel,cell} UF_{fuel} ex_{chemical}) - (\dot{m}_4 ex_4 - \dot{m}_3 ex_3)} \tag{8}$$

In the same way as was done for the fuel cell, the energy balance, entropy and consumption of combustor and presented in accordance with the Eq. (9) to (13).

$$\left(\dot{m}_3 + \dot{m}_{fuel,cell} . UF_{fuel}\right) h_4 + \dot{Q}_{comb} - \dot{m}_5 h_5 - \dot{Q}_{losses} = 0 \tag{9}$$

$$\dot{Q}_{losses} = (m_{fuel,cell}(1 - UF_{fuel}) + m_{fuel,comb})(1 - \eta_{comb})LHV_{fuel} \tag{10}$$

$$\dot{S}_{ger,comb} = \dot{m}_5 s_5 - \dot{m}_4 s_4 - (\dot{m}s)_{fuel,comb} + \frac{\dot{Q}_{losses}}{T_{surr}} - \frac{\dot{Q}_{comb}}{T_{comb}} \tag{11}$$

$$\begin{aligned} Ex_{dest,comb} = {} & \dot{m}_4 ex_4 + \dot{m}_{fuel,cell}(1 - UF_{fuel})ex_{chemical} + \\ & + \dot{m}_{fuel,comb}(ex_{physical} + ex_{chemical}) - \dot{m}_5 ex_5 - (1 - \frac{T_1}{T_{adiab}})\dot{Q}_{losses} \end{aligned} \tag{12}$$

$$\eta_{II,comb} = \frac{(\dot{m}_5 ex_5 - \dot{m}_4 ex_4)}{\dot{m}_{fuel,cell}(1 - UF_{fuel})ex_{chemical} + \dot{m}_{fuel,comb}(ex_{physical} + ex_{chemical})} \tag{13}$$

Finalizing the model and done the balance of mass, energy, entropy and consumption of the cycle as a whole, where we calculated the income and the generations of entropy and consumption destroyed for the entire cycle GT-SOFC according to Eq. (14) to (20) .

$$\dot{m}_4 = \dot{m}_3 + \dot{m}_{fuel,cell} UF_{fuel} + \dot{m}_{fuel,cell} \cdot \left(1 - UF_{fuel}\right) \tag{14}$$

$$\dot{m}_1 h_1 + \dot{m}_{fuel,cell} UF_{fuel} LHV + \dot{Q}_{comb} - \dot{m}_8 h_8 - \dot{Q}_{losses} = \dot{W}_{TP} + \dot{W}_{cell,DC} \tag{15}$$

$$\dot{W}_{cycle} = \eta_{inv} \dot{W}_{cell} + \eta_{ger} \dot{W}_{TP} \tag{16}$$

$$\dot{Q}_{total} = \dot{Q}_{comb} + \left(\dot{m}_{fuel,cell} UF_{fuel} LHV_{fuel}\right) \tag{17}$$

$$\eta_{cycle} = \frac{\dot{W}_{cycle}}{\dot{Q}_{total}} \tag{18}$$

$$Ex_{dest,cycle} = \dot{m}_1 ex_1 + \dot{m}_{fuel}(ex_{physical} + ex_{chemical}) - \dot{m}_8 ex_8 - \dot{W}_{cycle} \tag{19}$$

$$\eta_{II,cycle} = \frac{\dot{W}_{cycle}}{\dot{m}_{fuel}(ex_{physical} + ex_{chemical})} \tag{20}$$

The data standards for basic operation of the cycles are those listed in Tab. 4 were used for the cycle Brayton regenerative as well as for the GT-SOFC hybrid cycle. In the Tab. 4 are related defaults for operation of the fuel cell type solid oxide was used only for the GT-SOFC. For the calculation of entropy generation and destruction of exergy, it is necessary to calculate the adiabatic flame temperature and the exergies chemical and physical for the calculation of consumption destroyed, as Çengel and Boles (2006) and Wark (1995)

The general parameters of operation of the fuel cell and which were only used in the simulation of GT-SOFC hybrid cycle, where the majority of the cell parameters are obtained directly from the literature, such as, for example, the Handbook of fuel cells EG&G Technical Services (2004) and the textbook of Larminie (2003)

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Table 4 - Parameters of operation used in two cycles evaluated.

Operating Parameters	**Values**	**Operating Parameters**	**Values**
Inlet Pressure	101.35 kPa	Utilization factor of air	0.25
Ambient Temperature	288 K)	Fuel Usage Factor	0.85
Inlet Temperature TG	1250 K	Battery Temperature	1273 K
Adiabatic Temperature	250 K	Current density	300
Pressure Ratio	4	Eo	1.01 [V]
Efficiency compressor	0.81	Acelula	834 (cm^2)
Efficiency combustor	0.98	Faraday	96496 [Columb/kmol]
Efficiency TG	0.84	R	(8.314 kJ/kmol-K)
Efficiency TP	0.89	Kp	1.96X10140
Generator Output AC	0.95	The	0.02
Effectiveness recuperator	0.8	B	0.5
LHV Methane	50050 (kJ/kg)	Normal density - j	0.04
Pressure Losses Recuperator	4%	Maximum density - j1	1000
Pressure Losses Stack SOFC	4%	Specific resistance -j0	2X10-3
Pressure Losses Combustor	5%		

4. RESULTS AND DISCUSSION

The simulation were carried out analyzes of GT-SOFC hybrid cycle, which was inserted in the cell cycle the fuel, as the mathematical model described above. In the case of GT-SOFC hybrid cycle were carried out basically the same analyzes, but noting especially the influence of cell to fuel the mass balance, energy and exergy.

Initially, the simulation was applied to the Brayton regenerative cycle, Fig. 1 (a), in order to provide in addition to a comparative analysis as the results of the simulation of GT-SOFC hybrid cycle, Fig. 1 (b), the validation of the mathematical model.

Table 5. Results for the Brayton regenerative cycle for parameters pr=4 and TIT= 1100K.

Results Obtained	Values
Power to drive compressor	716.00 kW
Mass flow rate of fuel	0.0324 kg/s
Thermal power of the combustor	1623 kW
Thermal efficiency of the cycle	30.00%
Net Power of the cycle	488.30 kW
Entropy generation rate of the cycle	1.97 kW/K

Table 6. Results for the GT-SOFC hybrid cycle for parameters pr=4 and TIT= 1100K.

Results Obtained	Values
Thermal efficiency of the cycle	62.16%
Thermal power of the combustor	1316,0 kW
Mass flow rate of fuel in cell	0.0645 kg/s
Mass flow rate of fuel in combustor	0.0166 kg/s
Flame Adiabatic Temperature	2547 K
Power fromSOFC	2060 kW
Net Power of the cycle	2524 kW
Power to drive compressor	716.0 kW
Entropy generation rate of the cycle	2.097 kW/K

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Comparing the results for the efficient cycles of 30% for the Brayton regenerative and 62% for the GT-SOFC with the results obtained by Haseli et al. (2008) it can be observed in Fig. 2 a good concordance between the results especially with the variation of the pressure ratio, demonstrating the validity of the mathematical model proposed in this work.

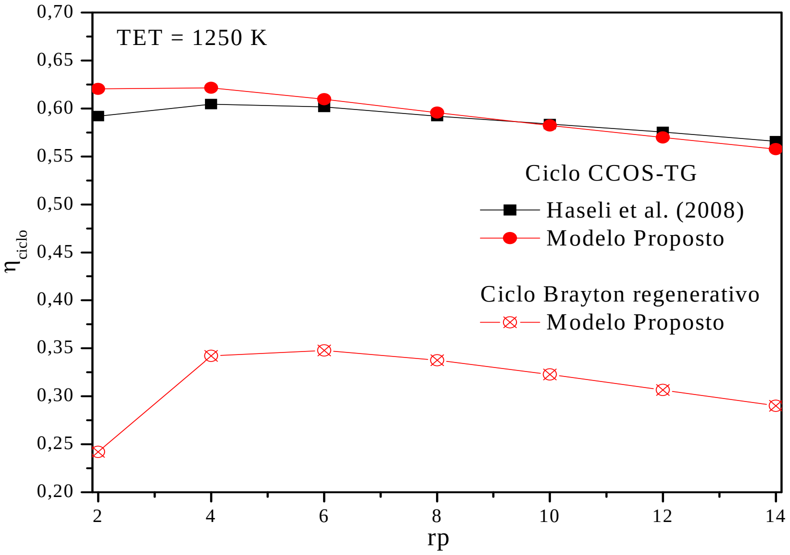

Figura 2. Comparison with Haseli et al. (2008) model

A second comparison is made through the exergy detruction rate, Fig. 3, where there is a slight variation due to the model of the calculation of properties thermodynamic and the software used in this work (EES) and the software used for (Haseli, Dincer et al. 2008) (MATLAB).

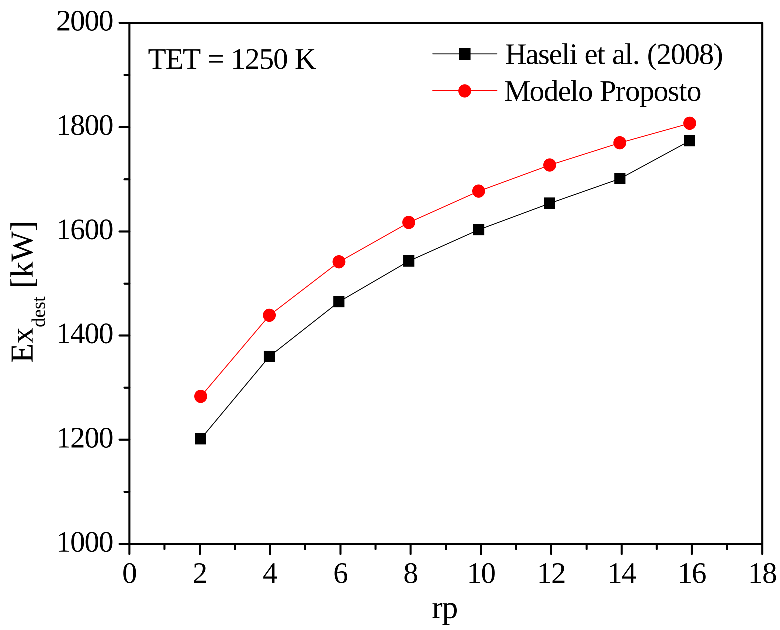

Figure 3. Comparison with Haseli et al. (2008) model for exergy destruction rate

It is also observed that the pressure ratio has greater influence on the reduction of efficiency exergetic, being that the higher efficiency is obtained for pressure ratio equal to 4.Figure 1.10 shows a comparison between the destruction of exergy there is a good agreement between the results obtained with the proposed model and those obtained by the model of Haseli et al. (2008) being the difference between the models for the destruction of consumption as a function of pressure ratio was on average approximately 4.5%, such difference may be associated with the models used for the calculation of thermodynamic properties.

Performing a comparative, shown in Tab. 7, between the results of the model proposed in this work and the results obtained by the work of Haseli et al. (2008) and Tse et al. (2007) that were basis for the development of the research, it was observed that a good concordance between the main parameters of COCS cycle-TG.

Table 7. Comparative results between the model proposed in this work and the models of Haseli et al. (2008) and Tse et al. (2007)

Result of Parameters	Unit	This study	Haseli et al.	Tse et al.
Pressure ratio	-	4	4	4
Inlet temperature of the gas turbine	K	1250	1250	1250
Thermal efficiency of the plant	%	62.16	60.55	59.40
Efficiency exergetica	%	58.15	57.90	-
Destruction of Exergy	kW	1441,00	1360,00	-
Specifies power compressor	kJ/kg	173.66	175.70	174.00
Specific power generator	kJ/kg	172.76	146.40	158.00
Specific power SOFC	kJ/kg	491.94	437.50	440.00
power Specifies total	kJ/kg	600.20	583.90	598.00
Power of the network	kW	2524,00	2419,30	2457,40
Air mass flow rate	kg/s	4.123	4.123	4.110
Fuel mass flow combustor	kg/s	0.0166	0.0172	0.0177
Flow Mass fuel cell	kg/s	0.0645	0.0626	0.0645

5. CONCLUSION

The present study showed a thermodynamic model of a GT-SOFC hybrid cycle which includes an analysis of both energy as exergy. The results of the model proposed in this work for the GT-SOFC hybrid cycle were compared with those obtained by Haseli, DincerHaseli et al. (2008) and Tse et al. (2007) which showed good concordance demonstrating the validity of model. A comparative analysis between the results for the GT-SOFC hybrid cycle and those obtained for cycle Brayton regenerative was also performed, demonstrating an increase in the power of your network in order to 71 %.

The main parameters analyzed were the pressure ratio (pr) and the inlet temperature of the gas turbine (TIT), because they directly affect the efficiency and production of power of these cycles and are among the main design parameters. It was observed that this analysis that the pressure ratio equal to 6 and the inlet temperature of the gas turbine of 1250K represent the best operating conditions for the cycle.

A big step so that they can occur significant changes with respect to the fuel cells would be the search for greater incentives in respect of experimental studies, where it is flanked the part of project of the cell in the search of new materials, thus the use of systems with micro-gas turbines that are still equipment found only in the external market. The GT-SOFC hybrid cycle is a promising technology that deserves greater investments for which the same can be disseminated in the market, since in addition to the aspect of improvement in efficient has the most important aspect of new sources of renewable energy generation that is the environmental aspect, where the level of CO_2 emissions are considerably lower than the conventional system of the gas turbine.

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