COMBINED SOFC AND GAS TURBINE CYCLES: A REVIEW

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Abstract. *Fuel cells appear to be very attractive power generation systems, promising highly efficient electricity generation with very low negative effects to the environment. These efficiencies can be further increased by integration of high temperature fuel cells SOFCs (solid oxide fuel cell) into hybrid cycles. Hybrid fuel cell systems are combinations of conventional heat engines (e.g., gas turbines, steam turbines, etc.) with different types of fuel cells or even combinations of two different types of fuel cells. These aforementioned systems are extremely efficient. They have the potential of achieving efficiencies near or even higher than seventy percent. This also means that they can be environmentally friendly due to their reduced level of emissions. They can be considered a perfect match for stationary applications (centralized or distributed), however, there are significant difficulties in utilizing them in mobile and vehicular applications due to issues related to their initial cost. Fortunately, during the last few years this cost has been dropped significantly with the use of cheaper materials and it is expected to drop even more with the increase of the mass production and commercialization of these systems. Further, due to the high full and part load efficiencies the operating cost of these systems is already lower compared to conventional power generating systems. Theoretical studies of combined SOFC and gas turbine cycles (SOFC-GT) have been conducted by several researchers and have been contributed to increase the attention worldwide,by this kind of system. These research works have presentes unbiased evaluation of the performance prospects and the operational behavior of such systems. There are several other previous studies in the literature involving the thermodynamics analysis, design and performance models. A comprehensive literature survey revealed only a few research articles that have studied irreversibilities of a combined SOFC-GT cycle by applying the second law of thermodynamics. This paper presents a literature review of research works performed by many researchers concerning various aspects of solid oxide fuel cells (SOFC) and gas turbines for stationary power applications.*

Keywords: *gas turbine, fuel cell, SOFC-GT cycle.*

1. INTRODUCTION

Fuel cells appear to be very attractive power generation systems, promising highly efficient electricity generation with very low negative effects to the environment. These efficiencies can be further increased by integration of high temperature fuel cells SOFCs (solid oxide fuel cell) into hybrid cycles. Hybrid fuel cell systems are combinations of conventional heat engines (e.g., gas turbines, steam turbines, etc.) and different types of fuel cells or even combinations of two different types of fuel cells. These aforementioned systems are extremely efficient. They have the potential of achieving efficiencies near or even higher than seventy percent. This also means that they can be environmentally friendly due to their reduced level of emissions.

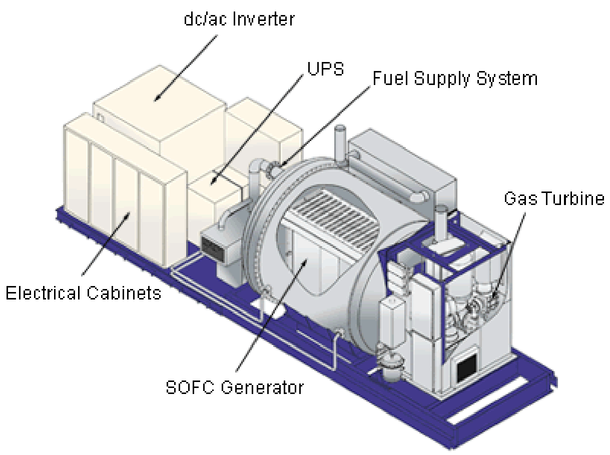
Hybrid fuel cell systems are a perfect match for stationary applications (centralized or distributed) while there are still significant difficulties in utilizing them in mobile and vehicular applications due to issues related to their primary cost. Fortunately, however, during the last few years, this cost has been dropped significantly with the use of cheaper materials and is expected to drop even more with the expected increase of mass production and commercialization of these systems. Also, due to the high full and part load efficiencies, the operating cost is already lower compared to conventional power generating systems. Theoretical studies of combined SOFC and gas turbine cycles (SOFC-GT) have attracted the attention of several researchers. The overall goal of these researchers was to provide an unbiased evaluation of performance prospects and operational behavior of such systems. There are several other previous studies in the literature involving the thermodynamics analysis, design and performance models. A comprehensive literature survey revealed only a few research articles that have studied irreversibilities of a combined SOFC-GT cycle by applying the second law of thermodynamics.

A hybrid power system combining a solid oxide fuel cell (SOFC) and a gas turbine (GT) cycle has the potential for very high efficiency in converting fossil fuels to AC electricity. The hybrid system offers two important and attractive features: (i) the increasing of the efficiency when compared to simple cycle fuel cell systems; (ii) the improving of the efficiency and the reduction of pollutants emissions simultaneously compared to conventional gas turbine power systems. The SOFC-GT hybrid systems have been considered for a large number of power generation applications, e.g., distributed generation and on-site power plants. The SOFC-GT hybrid systems also can be integrated with a gasifier to form highly efficient coal-based central generation power plants.

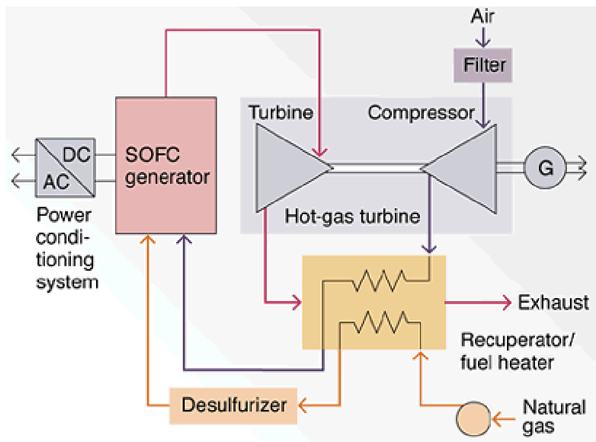
This paper presents a literature review of research works conducted by many researchers concerning various aspects of a solid oxide fuel cell and gas turbine for stationary power applications. Further, this paper discusses the development of SOFC technology for hybrid systems, presents several examples of hybrid system concepts and their performance characteristics, and identifies key technical challenges.

2. A BRIEF LITERATURE SURVEY

The ability to use both gas turbines and/or steam turbines in a combined cycle with a SOFC has been known in concept for many years. However, it is only recently that pressurized operation of SOFC stacks has been demonstrated for prolonged periods, making the SOFC-GT combined cycle system feasible practically. Pioneered by Siemens Westinghouse in their SureCell^{TM} concept, the idea of combined SOFC-GT is now being explored by other developers. Figure 1(a) shows the concept of design of the Siemens Westinghouse at the 300kW plant, while Figure 1 (b) shows the diagram with the essential processes of the plant. These systems and variations on them, are further described in the literature for Veyo and Forbes (1998), Bevc (1997), Fry *et al.* (1997), and Hassman (2001). The first complete SOFC-GT system was delivered by Siemens Westinghouse to the Southern Californian Edison Electricity Utility on May 2000. A second hybrid system was built by the Canadian Company Ontario Hydro, as well as, other units are being built by customers in Europe.



(a) The SOFC is shown in the middle of the diagram, and operates at about 10 bar inside the cylindrical pressure vessel. The gas turbine, compressor, and alternator are behind the fuel cell.



(b) System diagram for the 300kW class SOFC-GT hybrid cycle system.

Figure 1. Design of a 300kW class MW SOFC-GT combined cycle plant built by Siemens-Westinghouse.

The expected performance data for both the 300 kW class and 1 MW class hybrid systems are shown in Table 1. The systems having higher capacities also have potential to operate with higher pressures. For example, SOFC cells of hybrid systems having 2 MW to 20 MW of capacity, and working with air and fuel injection pressure of 700 kPa, would increase their efficiency in the range of 60 to 70%, respectively. However, this more sophisticated GT system would require additional investment, which may not be justified due to the small increase of their efficiency. On the other hand, conform presents Table 1, the emissions of CO_2 for the 300 kW and 1 MW hybrid systems shows to be the same. This fact proves the great advantage of hybrid cycles for the all applications (i.e., centralized or distributed energy power). The Siemens Westinghouse has many projects in different countries as well as research centers. Table 2 presents a demonstration summary of the activities developed by Siemens in these countries. The first pre-commercial product developed by Siemens Power Generation will be the SFC-200, which is a 125 kW SOFC cogeneration system, operating with natural gas at atmospheric pressure, with electrical efficiency in the range of 44% to 47% at full load. The next generation SOFC developed by Siemens Power Generation is called "SECA" (Solid State Energy Conversion Alliance),conforms Vora (2003) that has conducted research in new materials, cost reduction, improved manufacturing processes and HPD (high power density) seal-less planar cell designs. A number of these seal-less planar high power density (HPD) cell prototypes have been fabricated, and tests are being conducted to evaluate their performance.

Table 1. Expected performance of Siemens Westinghouse 300 KW and 1MW class Hybrid Systems (Larminie (2003))

	300 kW	**1 MW**
Electrical net AC efficiency	>55%	> 55% approaching 60%
SOFC AC power	244 KW	805 KW
Gas turbine AC power	65 KW	220 KW
Total net AC power	300 KW	1014 KW
Pressure ratio of turbine / compressor	3 / 4	3 / 4
Emissions: CO_2	< 350 Kg MWh^{-1}	< 350 Kg MWh^{-1}
NO_x	< 0.5 ppm	< 0.5 ppm
CO	0 ppm	0 ppm
SO_x	0 ppm	0 ppm
Particulates	0 ppm	0 ppm
Ground noise level (5 m from housing)	< 75 dBa	< 75 dBa

In accordance with Table 2, available in the Siemens web site, Siemens (2007), it is possible to analyze some details of the history of tests considering the demonstrations of various types of cells that have already been built by Siemens.

Table 2. Summary of Tests and Demonstrations for SOFC.

Year	**Customer**	**Stack Rating (kWe)**	**Cell Length (mm)**	**No. of Cells/Stack**	**Oper. (Hrs)**	**Fuel**
1986	TVA	0.4	300	24	1760	H2+CO
1987	Tokyo Gas	3	360	144	4882	H2+CO
1987	Osaka Gas	3	360	144	3683	H2+CO
1987	Osaka Gas	3	360	144	3012	H2+CO
1992	Utilities-B1	20	500	576	1579	PNG
1992	Utilities-A	20	500	576	2601	PNG
1992	JGU-1	20	500	576	817	PNG
1993	Utilities-B2	20	500	576	7064	PNG
1994	SCE-1	20	500	576	6015	PNG
1995	JGU-2	25	500	576	13194	PNG DF-2 JP8
1995	SCE-2	27	500	576	5582	PNG
1997	EDB/ELSAM-1	125	1500	1152	4035	PNG
1998	SCE-2/NFCRC	27	500	576	5700+	PNG
1999	EDB/ELSAM-2	125	1500	1152	12,577	PNG
2000	SCE PSOFC/GT	180	1500	1152	3257	PNG
2001	RWE	125	1500	1152	3872	PNG
2002	OPT	250	1500	2304	1000+	PNG
2005	SW Hannover	125	1500	1140		PNG
2006	BP Alaska	125	1500	1140		PNG

From Table 2 it can be observed that the fuel used since 1992 is notoriously the pressurized natural gas (PNG) and it is already consolidated as the fuel that achieves the better performance. The tests also show that the area and the number of cells in stack obtained improvements during the last decades. Despite the proven mathematical models available in the literature there is still a demand for research looking for improvements mainly regarding the economic aspects as well as the construction of combined cycle. The energy density by area of the cell is still a parameter that needs to be well explored through the investigation of new materials and formats. Also in accordance with the testing of Table 2, another aspect that needs to be assessed is the question of life cycle of the SOFC, regarding their time of operation, as well as, the cost of maintaining, and stakes of the system due to the cell.

Despite the development of business units of power generation using hybrid system of the type of SOFC-GT, Figure 2 (from the database of Web of Science, which brings together many scientific journals), shows that during the period of 1998 to 2008 the number of articles published referent to hybrid systems SOFC-GT was irregular and the peak of publications occurred in 2006. Such behavior may be associated to the energy crisis at that time which demanded research for new sources that could generate less environmental impact. It can be figured out from the graphic notes of Figure 2 that this decrease in research also can be attributed to the economics and the search of solutions though other clean energy sources that appeared more viable. Also, it can be observed that most of the technical articles have been focused on developing mathematics models for the cells and not specific models aimed for the components of the cycle.

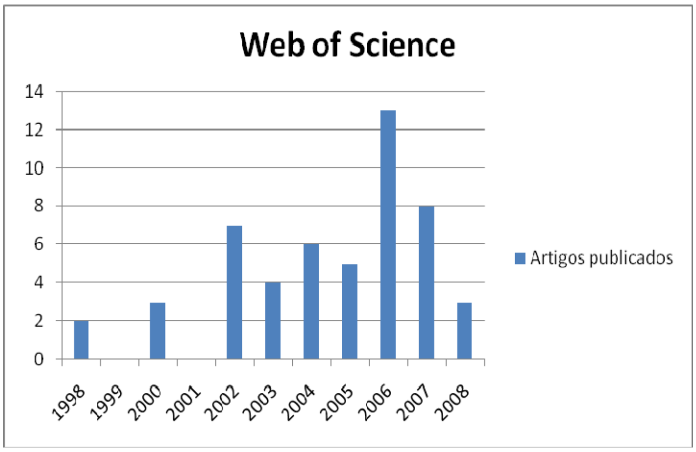


Figure 2. Graph of the lifting of the articles published from 1998 to 2008.

A comprehensive literature survey revealed only a few research articles that have studied irreversibilities of a combined SOFC-GT cycle by applying the second law of thermodynamics, such as studies performed by George (2000), Costamagna *et al.* (2004), Chan *et al.* (2003), Calise, D'accadia *et al.* (2006), based on the first and second laws of thermodynamics. An exergy analysis was presented by Haseli *et al.* (2008) to find the thermodynamic losses in each component and assess the work potentials of the different streams and heat interactions. It also have been observed from Figure 2 that the experimental work is very reduced, highlighting among these the work of Lai *et al.* (2007). Table 3 summarizes different values of thermal efficiency, which were obtained from studies of different researchers.

3. MODELING APPROACHES

In recent years several groups have presented results on the modeling of hybrid SOFC-GT systems. It can be mentioned past works of , Rokni (1993), and Harvey and Ricther (1994). Also the Italian groups of Massardo and Lubelli (2000), and Campanari and Macchi (1998) were published related to systems studies, as well as, work developed by the group constituted from Rolls-Royce, Stephenson and I. (1997). Recently other studies regarding systems were published by Calise, Palombo *et al.* (2006), Calise, D'accadia *et al.* (2006) and Haseli *et al.* (2008).Different approaches have been used to design the investigated systems, the type of fuel, and modeling approach. Consequently, the results presented differ, ranging from an electric efficiency of 55% for small-scale systems to 77% for larger power plant systems.

In hybrid SOFC-GT systems the mathematical modeling of fuel cells is, in general, complicated because it includes electrochemical representation of the cells (transport phenomena and thermodynamics of the systems), and different mathematical techniques also have to be applied to solve the numerical computations, once that the resulting equations are coupled and highly non-linear. Normally, these equations are linearized and transformed into finite difference or element approximations and solved with well-know techniques. The utility of these codes depends partly on the efficiency of the convergence routines applied to iterative computations, and partly on the type of simplifications that can be introduced without offset the accuracy and generality of the method.

Table 3. Survey of thermal efficiencies of combined SOFC–GT plants in past literature

System Configuration	**Efficiency**	**Reference**
Pressurized cycle using an SOFC and integrated GT bottoming cycle	68.1	Harvey and Ricther (1994)
Pressurized SOFC–GT combined cycle	60–65	George (1997)
Pressurized SOFC–GT cycle with a heat recovery bottoming cycle	70<	Campanari and Macchi (1998)
Recuperated micro gas turbine (MGT) with a high temperature SOFC	60<	Costamagna *et al.* (2001)
SOFC stack, combustor, GT, two compressors and 3 recuperators	60<	Chan *et al.* (2002)
Pressurized tubular SOFC combined with an intercooled-rehear GT	66.23	Rao and Samuelsen (2003)
Dual SOFC–HAT hybrid cycle	75.68	Rao and Samuelsen (2003)
Internal-reforming (IR) SOFC–GT power generation system	60<	Chan *et al.* (2003)
Combined SOFC–GT system with liquefaction recovery of CO_2	70.64	Inui *et al.* (2005)
IR tubular SOFC–GT plant with 3 heat exchangers and mixers	65.4	Calise, Palombo *et al.* (2006)
1.5 MW integrated IRSOFC with two GTs and one HRSG	60	Calise, D'accadia *et al.* (2006)
Two-staged low and high temperature SOFC power generation cycle	56.1	Araki *et al.* (2006)
Multi-staged SOFC–gas turbine–CO_2 recovery power plant	68.5	Araki *et al.* (2007)
Recuperated GT integrated with SOFC	59.4	Tse *et al.* (2007)
Recuperated GT with compressor air inter-cooling and two SOFCs	68.7	Tse *et al.* (2007)
Thermodynamic modeling of a GT cycle combined with a SOFC	60.6	Haseli *et al.* (2008)

Different levels of complexity of fuel cell model have been used by different authors, ranging from simplified or empirical to mathematical and validated models. Examples of woks using a simplified or empirical approach were presented by Stephenson and I. (1997), and Johansson *et al.* (1998), who used relations based on published performance curves from Siemens-Westinghouse. Many other studies employed a semi-empirical approach or a mathematical description combined with simplified assumptions. It can be emphasized the work developed by Campanari and Macchi (1998), that adopted published data for cell voltage and other experimental relations which were used to solve the governing equations. Lunghi and Ubertini (2001) developed a mathematical model, which consisted of a detailed electrochemical loss description; however, simplified assumptions also were utilized concerning the uniformity of the cell and gas temperatures, as well as, the current density distribution. The most advanced fuel cell models can, probably, be found in the works presented by Harvey and Richter (1994), Costamagna *et al.* (2001), Selimovic and Palsson (2002), Palsson *et al.* (2000), Braun (2002), and Calise *et al.* (2007).

In general the hybrid SOFC-GT systems models can be divided in three-dimensional, two-dimensional, one-dimensional and zero-dimensional. However, some models depend on the geometry of the cell: planar or tubular.

In the planar design, the components are assembled in flat stacks, with air and fuel flowing through channels built into the cathode and anode. On the other hand, in the tubular design, components are assembled in the form of a hollow tube, with the cell constructed in layers around a tubular cathode; air flows through the inside of the tube and fuel flows around the exterior surface. The stage of development of planar designs is older than the tubular ones. The planar designs are simpler to manufacture and consist of flat plates bonded together to form the electrode-electrolyte assemblies. Additionally, the planar design offers lower ohmic resistance and higher power densities compared to the tubular design, but typically it requires high temperature seals and it is not as robust (especially under pressurized conditions).

The tubular design is the most advanced and has being developed by Siemens Westinghouse, the world leader in solid oxide fuel cell technology. This design has reached the field unit demonstration phase of commercialization. Planar SOFC technology has contributed to delay the development of tubular technology, but developers are making good progress in issues related to the barriers of performance and cost, and some already have offered as a commercial product in 2002.

Past works of 3D models are described by Achenbach (1994), Bessette (1994), Recknagle *et al.* (2003), Bove and Ubertini (2005). This concept of model requires more detailed information of the cell, because an analysis is made in the three coordinated. It intends to represent all the processes that occur inside the cell, toward the channels of gases, in the direction of flow of ions and electrons through electrolyte and electrodes, as well as, the behavior of the temperature and current density in a third dimension of the cell.

In according to Bove and Ubertini (2005), the 2D models due the simplifications and hypothesis provides results as good as the 3D models, requiring less effort mathematical. The work published by Iwata *et al.* (2000), presents a 2D model to analyze a flat SOFC with counter flow and a 3D model to analyze cross flow.

The zero-dimensional models, also named “black box”, are simplified and the most utilized models. However, despite its simplicity, such models provide effective thermodynamics analysis in systems based on fuel cell due to its better numerical analysis. These different concepts of models take into account mathematical models for each component of the hybrid system, such as, compressor, heat recuperator, turbine, reformer and the cell fuel itself. Figure 3 shows a typical configuration for an integrated GT–SOFC, corresponding to the illustrated picture shown previously in Figure 1a.

Each component of the system is modeled separately considering “black box” types; however, there are several possible cycle configurations for the fuel cell and the gas turbine. The cycle is composed by six primary components: air compressor, recuperator, high-temperature Solid Oxide Fuel Cell (SOFC), combustor, gas turbine and power turbine.

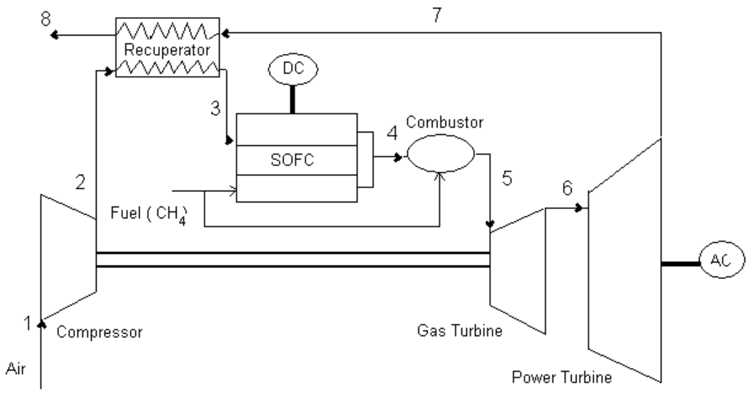


Figure 3. Schematic of a combined Gas Turbine power plant with an SOFC (Haseli *et al.* (2008)).

Air is pressurized by the compressor flowing through the recuperator, where it is preheated by the gas leaving the turbine, following its way to the SOFC cell. On the other hand fuel is pumped to the gas turbine, flowing though the SOFC cell, where it reacts electrochemically with the air inside the fuel cell, generating electricity and gases with high enthalpies. The high enthalpy exhaust gas is then mixed with to the bypassed fuel going to the combustion chamber (i.e. combustor) where the combustion occurs. The gas at high temperature and pressure leaving the combustor goes to the gas turbine (GT) providing work to drive the compressor. Then the expanded gas goes to the shaft turbine to generate electricity. It is observed from Fig. 3 that the waste heat from the fuel cell is utilized to increase the system efficiency, because the efficiency losses of the power generation processes is largely influenced by the highly irreversible fuel combustion process. Therefore, the efficiency can be improved if immediate contact between air and fuel is prevented, as it occurs in fuel cells.

The presentation of the models available in the literature for the components such as air compressor, recuperator, combustor, gas turbine and power turbine is not the goal of this paper. These models are based on thermodynamics, specifically mass, energy and entropy balances. Therefore, the objective of this paper is not to show equations and models for these components, rather to show the equations for modeling SOFC cells. The SOFC model described by Haseli *et al.* (2008) shows applies equations for the overall mass and energy balances of the fuel cell, which requires the evaluation of both the voltage and the current produced by the stack. The Eq. (1) shows the reagents and products of the electrochemical reaction in the cell.

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

The Eq. (2) is named the Nernst equation, where E_o is the ideal cell voltage at standard conditions, R is the universal gas constant, T is the stack temperature, P is the partial pressure and F denotes the Faraday constant (96,485 C/ mole).The Nernst equation provides a relationship between the ideal standard potential E_o, for the cell reaction and the ideal equilibrium potential E, at other temperatures and partial pressures of reactants and products.

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

The set of equations that follows, Eq. (3) to (5), presents the procedure to evaluate the cell irreversibilitties. It can be seen from Eq. (3), that the DC electric power $W_{FC,\,DC}$ depends on the current density j (the rate of electron transfer per unit activation area of the fuel cell), the cell voltage, V_c, and the cell area, A_c. The cell voltage, V_c, conforms shown in Eq. (4), is the ideal equilibrium potential, E, subtracted from ΔV_{loss} (i.e., the difference between the open-circuit voltage, obtained from Nernst equation, and the cell voltage losses). Eq. (5) shows the three components of the voltage losses in the fuel cell, where V_{act}, V_{ohm}, and V_{conc} are, respectively, the polarization, ohmic, and concentration losses.

$$\dot{W}_{FC,dc} = V_c . j . A_c \tag{3}$$

$$V_c = E - \Delta V_{loss} \tag{4}$$

$$\Delta V_{loss} = V_{act} + V_{ohm} + V_{conc} \tag{5}$$

The energy and entropy balances can be summarize in the equations (6) e (7), where the variables are: *LHV* lower heating value, $\dot{m}$ mass flow rate, *h* specific enthalpy, *s* specific entropy, U_f fuel utilization factor, S_{gen} entropy generation rate, $W_{FC;dc}$ DC power output of the cell stack, with the inlet and outlet flows in the presented in Fig. 4.

$$\dot{m}_3 . h_3 + \dot{m}_{fuel,FC} . U_f . LHV + \dot{m}_{fuel,FC} . (1 - U_f) . h_{fuel,in} - \dot{W}_{FC,dc} - \dot{m}_4 . h_4 = 0 \tag{6}$$

$$\dot{m}_3 . s_3 + (\dot{m}s)_{fuel,FC} + \dot{S}_{gen,FC} - \dot{m}_4 . s_4 = 0 \tag{7}$$

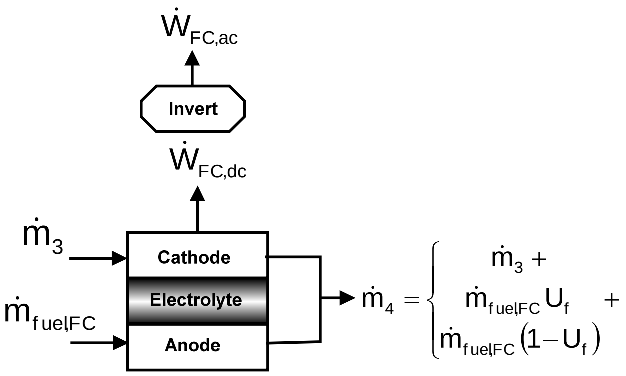


Figure 4. Schematic of the SOFC cell showing the inlet and outlet flows, Haseli *et al.* (2008).

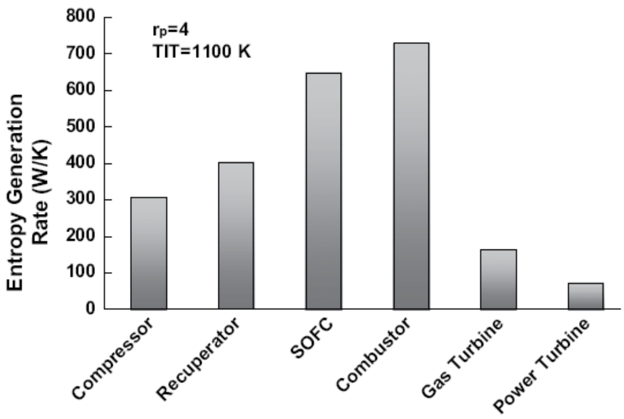


Figure 5. Entropy generation of the GT–SOFC plant components, by Haseli *et al.* (2008).

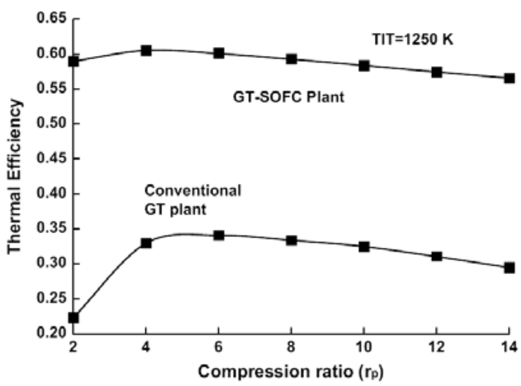
The most significant variables characterizing the cycle of Fig. 3 are the fuel cell operating temperature range, the temperature and pressure at the inlet of the gas turbine, TIT, (point 5). These variables are directly related to certain operating variables such as the air/fuel ratio entering the fuel cell, the fraction of the unburned fuel leaving the cell, and the temperature difference between the combustion products and the air at the high temperature leaving of the recuperative heat exchanger. The operating variables must be selected and controlled to allow effective operation of the fuel cell, combustor, and gas turbine, (Eg&G Technical Services (2004)). An important issue to be raised about the components is their contribution to the irreversibility of the hybrid cycle. Fig. 5 reports results issued by Haseli *et al.* (2008) about irreversibility in the different components of the hybrid cycle. It can be observed from Fig. 5 that the components that show the higher generation of entropy are the SOFC cell and the combustor.

The main advantages of hybrid system include a simple cycle arrangement with a minimum number of components, low compressor and turbine pressure ratio, low fuel cell operating pressure, low turbine inlet temperature without turbine rotor blade cooling, simple heat removal arrangements for the SOFC, maximum fuel cell conversion, and compatibility to small scale power generation systems.

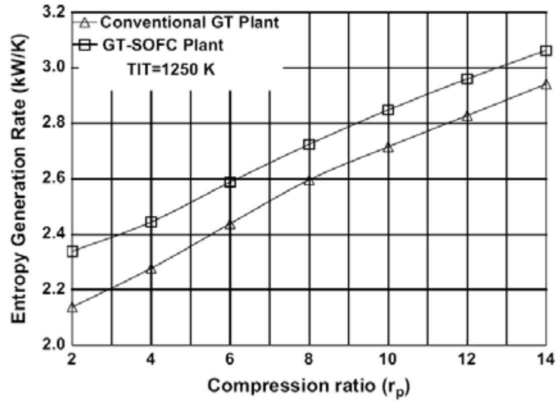
The main disadvantages of hybrid systems are the need of rigorous compressor and turbine design compatible with SOFC requirements, the need for a large gas to gas heat exchanger for high temperature heat recuperation, and the total efficiency and net work output of the system, which are sensitive to the efficiencies of the SOFC cell, gas turbine, compressor, as well as, the, pressure losses and temperature differences.

4. COMPARASION

A comparison has been performed between the efficiencies of conventional gas turbine cycle and non conventional hybrids SOFC-GT cycle. It can be observed the great advance in fuel cell technology and its potential to become available commercially in the next years. Also the cost of this hybrid system is dropping and in the near future can entirely feasible in both economic aspects of maintaining and useful life time of the plant. Figs. 6 and 7 refer to the studies conducted by Haseli *et al.* (2008). It can be observed from Fig. 6 that the thermal efficiency, Fig. 6(a) and entropy generation rate, Fig. 6(b), of the SOFC-GT system is higher compared to the turbine conventional cycle. The SOFC-GT system presents higher values of entropy than those of conventional system, however, it shows higher efficiencies values than those carried out by the conventional cycle.



(a) Thermal efficiency



(b) Entropy generation rate

Figure 6. Comparison between a conventional GT cycle and a GT-SOFC hybrid cycle, by Haseli *et al.* (2008).

Figure 7 shows a comparison of one relevant aspect, which is related to the CO_2 emissions of the two cycles. The values of CO_2 emissions of the SOFC-GT system are much lesser than those presented by the conventional turbine cycle. It also can be noticed from Fig. 7 that as the compression ratio (r_P) decreases the difference of CO_2 emissions, between the conventional and hybrid systems, becomes higher due to the reduction of efficiency of the turbine cycle (Fig. 6). The emissions of the SOFC-GT system seems to be not sensitive to the change of the compression rate, due to the stable performance condition of this type of system, even for large sizes of plants produced as shown in Table 1 by Siemens (2007).

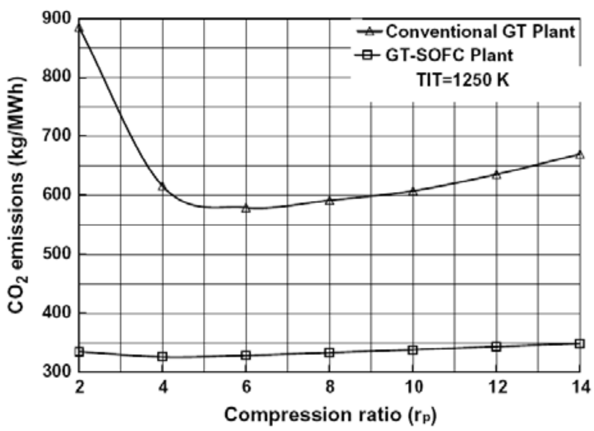


Figure 7. Comparison between a conventional GT plants with a GT-SOFC cycle hybrid. Haseli *et al.* (2008).

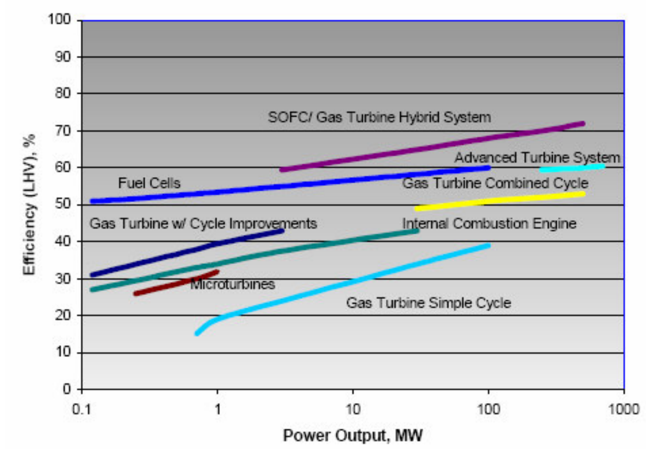


Figure 8. Estimated Efficiency of Different Power Generation Systems, by Eg&G Technical Services (2004)

On the other hand Fig 7 emphasizes that the conventional system has a strong dependence of the compression rate that also affect both the efficiency and the CO_2 emissions. From the various papers available in the literature it can be concluded that the great challenge to be overcame is the system cost of the hybrid systems, which is related to the high installation cost per kW of generated electrical power. The literature review points out a fall in these costs values from the year 2000 until mid of 2008 around 50%. Nowadays conventional technology is approximately ten times cheaper than hybrid technology. Therefore, it seems essential to have a hybrid SOFC-GT plant system running in order to validate existing studies, as well as, to evaluate important aspects such as the life cycle and the costs of maintenance and operation. The decrease of the specific value of installed kW of SOFC-GT system is already a great step and can contribute to the consolidation of hybrid systems. These systems also can become a good promise being capable of generating a cleaner power to attend the environmental concerns and needs of the society.

5. CONCLUSIONS

The objective of the present paper was to perform a literature survey of the SOFC-GT hybrid systems. It was verified the potential of the GT-SOFC hybrid cycle for application in the near future. After this bibliographic review it could be perceived that the most important at this moment is to invest in experimental studies for this type of system in order to validate proposed and new models, as well as, to help the developing of economic studies. Recent works were published like the Arsalis (2008) paper that presented studies of hybrids cycles plants in the range of 1.5 to 10MWe. Also experimental studies were performed in Korea by Lim *et al.* (2008). These studies are the most currently published works about SOFC-GT hybrid systems. An overview of different power generation systems is presented in Fig. 8, referent to the work published by Eg&G Technical Services (2004). It can be concluded that SOFC-GT, as presented in Fig 8, is really the best option considering its higher efficiency compared to the other systems. The incorporation of the SOFC cell in the turbine cycle can be pointed out as the main reason for the higher efficiency. Stand alone fuel cell systems is not viable despite its good efficiency. However, when it is combined with gas or steam turbine cycles, or the two together, a better performance can be achieved due to the integration of all the components of the cycle.

SOFC-GT hybrid system has a very promising future for distributed generation, mainly for the industrial sector, that cannot suffer lack of energy, which occurs in most cases due to failures in the network transmission. The advantages of this system outweigh in many respects the conventional system. Therefore, the demand for hybrids cycles in the industrial sector had a considerable increase in the last decades because of the environment concerns and demand for energy and cost savings. The SOFC-GT system may contribute in many aspects to increase the thermal efficiency of power generation systems.

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