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# Analysis and optimization of hybrid MCFC gas turbines plants

Piero Lunghi*, Roberto Bove, Umberto Desideri

*Dipartimento di Ingegneria Industriale, Università di Perugia, Via G. Duranti 93-06125 Perugia, Italy*

**Abstract**

High temperature fuel cells are electricity producers that guarantee relevant energetic and environmental performances. They feature high electricity to input chemical energy ratios and availability of high temperature heat.

Notwithstanding, the search for a further increase in electric efficiency, especially when applying a CHP solution is not feasible, has brought to plant integration with gas turbines (GTs) in several studies and some pilot installations. While for pressurized fuel cells the choice of internal combustion gas turbines seem to be the only one feasible, in ambient pressure fuel cells it seems useful to analyze the combination with indirect heated GT. This choice allows to optimize turbine pressure ratio and cell size.

In this work, a parametric performance evaluation of a hybrid molten carbonate fuel cell (MCFC) indirect heated gas turbine has been performed by varying the fuel cell section size and the fuel utilization coefficient. The analysis of performance variation with the latter parameter shows how a cell that is optimized for stand alone operation is not necessarily optimized for the integration in a hybrid cycle. Working with reduced utilization factors, in fact can reduce irreversible losses and does not necessarily yield to less electricity production since the heat produced in the post combustor is recovered by the gas turbine section. This aspect has not been taken into sufficient consideration in literature.

The analysis illustrates the methodology to define new operating conditions so to allow global output and global efficiency maximization.


*Keywords:* MCFC; Indirect gas turbine; Hybrid cycles; High efficiency

## 1. Introduction

The main energy source for power generation is worldwide represented by fossil fuel. In particular, in 1995, about 60% of the electricity power has been produced using natural gas, fuel oil and coal, while only 23% of the energy has been produced using renewable source [1]. The use of non-renewable source of energy brings to two main environmental disadvantages: the increase of both raw material depletion and the rising of air pollution because this practice is often obtained by combustion. These two problems can be reduced with a better use of energy resources, including a more rational use of renewable ones, and realizing energy conversion devices with high conversion efficiency. Consequently, efficiency represents not only an indicator of careful treatment of natural fuel resource, but it represents even a pointer of air pollution to produce a reference amount of energy.

Moreover high efficiency is linked to economic benefits. A generally accepted way to increase efficiency is to combine cycles. In the present work molten carbonate fuel cell (MCFC) plant, whose cycle alone presents a high electric efficiency, is combined with a small size gas turbine (GT).

This plant configuration has previously been studied [2–4]. In [2], a preliminary study was conducted in order to find, among different bottoming cycles, the most promising one. The cycle was an external combustion gas turbine, because this solution allows to use ambient pressure fuel cell stacks that present high simplicity and low investment cost. A closed loop cycle has been considered, using different gas types. The most feasible gas was air. For this reason, in [3,4] the plant configuration scheme considered was open cycle gas turbine using air as the working fluid. In these two previous works, the optimisation of the GT cycle was conducted, considering the MCFC stacks with a fixed output power and coefficient of fuel utilization.

In literature, several technical analyses and simulations were conducted in order to predict the efficiency of hybrid plant comprised by high temperature fuel cell (SOFC or MCFC) and gas turbine [2–8] and the results of these studies is an estimation of the electric efficiency that can reach 75%. This value can be considered as a target, but it implies new designs for gas turbine, and so this value of plant efficiency is only potentially associated to new plants that could be constructed in future years. For the present commercial gas

* Corresponding author. Tel.: +390755853739.
*E-mail address:* lunghi@unipg.it (P. Lunghi).

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**Nomenclature**

| | |
|---|---|
| CoE | cost of electricity |
| GT | gas turbine |
| $h$ | specific enthalpy |
| HRSG | heat recovery steam generator |
| $I_{in}$ | electric current that could be produced if all the fuel would be converted (i.e. $u_f = 1$) |
| $I_{out}$ | electric current |
| $J_{out}$ | mean current density |
| $m$ | mass flowrate |
| MCFC | molten carbonate fuel cell |
| SOFC | solid oxide fuel cell |
| $u_f$ | coefficient of fuel utilization of the fuel cell |
| $V$ | cell voltage |
| $W_{cell}$ | output power provided by the fuel cell |

turbine, in fact, the inlet gas temperature (maximum temperature of the Brayton cycle) is quite higher than the outlet cathodic gas temperature, and so additional fuel has to be provided to the bottoming cycle. Being gas turbine efficiency lower than the fuel cell one, it is obvious that the more fuel supplied to the bottoming cycle and the lower is the plant electric efficiency. It is possible to feed no additional fuel to the gas turbine only if the exhaust gas temperature is particularly high and there is enough unburned fuel to reach the target temperature through combustion at the FC outlet [7]. In the present work, an MCFC–GT plant where the gas turbine is a commercial one is implemented. The temperature of the inlet gas is 1100 °C and so a combustion chamber is used to reach this temperature. For low value of $u_f$ no combustion is needed in the bottoming cycle; in any case, low $u_f$ means low MCFC efficiency. Numerical plant simulation is needed to estimate optimal $u_f$ and fuel cell size values for the whole plant efficiency analysis and optimisation.

Table 1
Main characteristics of the PGT-2 gas turbine

| | |
|---|---|
| Electric output (kW) | 2000 |
| Electric efficiency (%) | 26.3 |
| Exhaust temperature (°C) | 550 |
| Turbine inlet temperature (°C) | 1100 |
| Gas flowrate (kg/s) | 11 |
| Air flowrate for turbine refrigeration (kg/s) | 0.6195 |

The gas turbine is chosen following the results of [2,3]. Being GT a mature and consolidated technology, the optimal operating conditions of the bottoming cycle are well known. The optimisation of the plant is so conducted varying fuel cell parameters.

## 2. Plant layout

The fuel cell stacks are MCFC type with internal reforming and operating at ambient pressure. This type of technology allows to obtain high efficiency and high temperature exhaust gas, and therefore high efficiency combined power plant. As stated before, the gas turbine is a commercial one, produced by GE-Nuovo Pignone. The model is PGT-2, the main characteristics of which are reported in Table 1. The configuration of the whole plant is schematically reported in Fig. 1.

The fuel used is natural gas. The presence of sulphur in the commercial available natural gas must be reduced to a limit of about 100 ppbv [9]. This achievement can be obtained using alluminia and zinc oxide beds [10]. This unit is schematically represented and denoted as "gas treatment unit". In order to obtain higher cell efficiency, the natural gas is pre-heated using the heat content of the cathodic gas, before entering the stacks. For this purpose a valve is used to

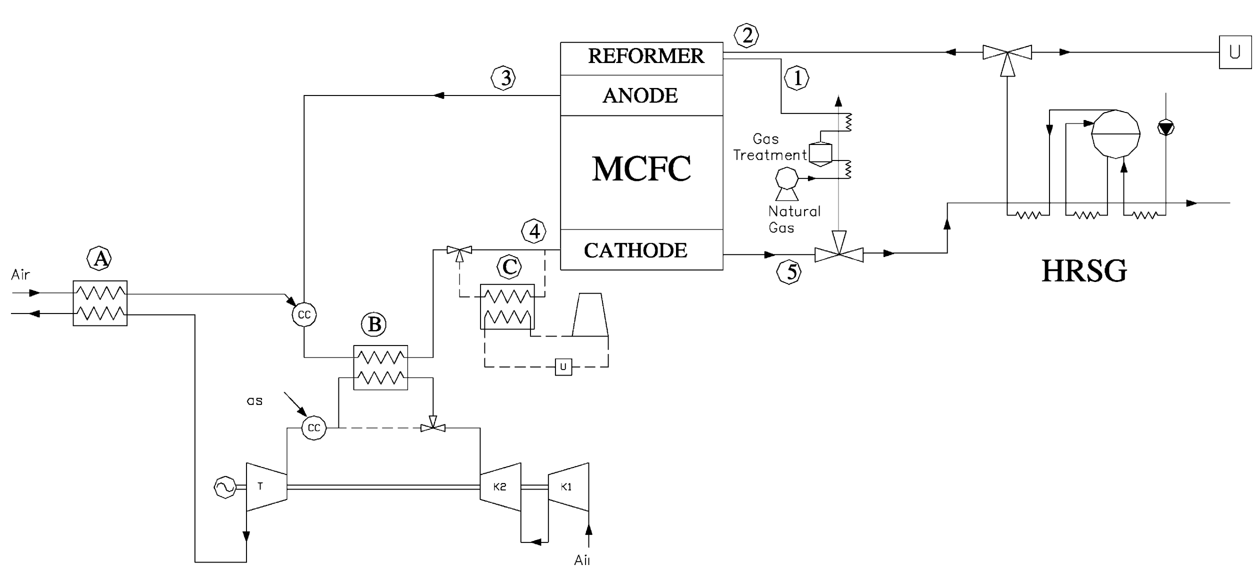


Fig. 1. Plant layout.

split the gas stream in two. These are used to: produce steam needed for the reforming process and pre-heat the fuel.

The anode exhaust gas exits the stacks and the unoxidized fuel is burnt in a catalytic combustor. After combustion and before re-entering the stack, the gas is cooled until the temperature reaches the optimal value required. The heat released is used in the bottoming cycle (heat exchanger B). In order to increase the plant's feasibility, the two sections can operate totally independently. For this purpose, a cooling system for the cathodic inlet gas is inserted (C). For the same reason, the heat exchanger that provides heat to the gas turbine cycle can be by-passed by the compressed air. The exhaust gas from the turbine is sent to the heat exchanger (A) that increases the temperature of the air supplied to the catalytic combustor. As can be noted from Table 1, the turbine inlet temperature is 1100 °C. If the temperature achieved after the gas passes the heat exchanger is lower, natural gas is burnt in a combustion chamber. Anyhow, as explained more thoroughly in the following, burning fuel in this combustion chamber leads to a reduction in electricity efficiency.

## 3. Plant simulations

The numerical simulations are carried out in order to find the optimal size and the operational parameters of MCFC, and consequently, the definition of the optimal size of the components of the plant (heat exchangers, HRSG, etc.) is carried out. The software used is *Aspen Plus*. All the modules forming the balance of the plant (BoP), i.e. gas turbine, compressors, heat exchangers, etc. have been simulated using the modules provided by the software. The MCFC performance is instead evaluated using a proprietary code implemented at the University of Perugia, by the authors [11] and integrated in *Aspen Plus*. This code allows to evaluate output gas flowrate, the cell voltage ($V$), the power produced ($W$) and the active surface of the stacks ($S$), for any coefficient of fuel utilization ($u_f$), current density ($J_{out}$), inlet gas stream composition and flowrate. In Fig. 2 the way of working of the MCFC block is represented [12]. The code has been validated through several tests conducted in the MCFC test rig of the University of Perugia [13].

The model used is an analytic one that for performance calculation takes into account oxidant and fuel characteristics (i.e. composition, flowrate and temperature), fuel and oxidant utilization and specific characteristics of MCFCs. Ohmic, activation and diffusion losses, together with shift reaction complete the model. As stated in [11] the model must be a compromise between results reliability and calculation simplicity. *Aspen Plus* software, in fact, uses iterative methods to solve equations that model the whole plant and so it uses the MCFC model several times. On the other hand, model prediction has to be a close as possible to real fuel cell performance. Tests conducted at the Laboratory of the University of Perugia, confirmed code reliability.

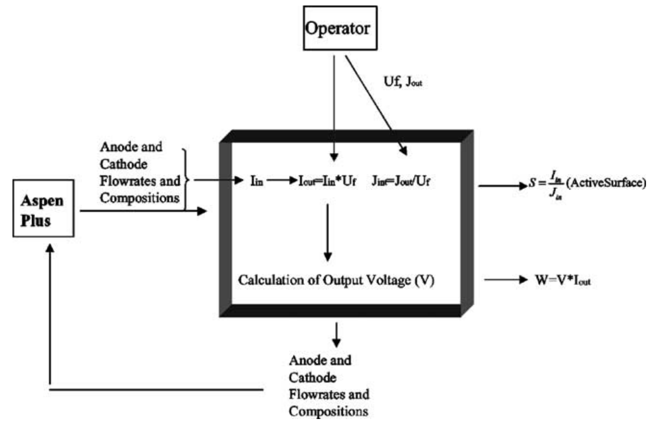


Fig. 2. Interaction between Aspen Plus and the proprietary fuel cell code.

For more details about code structure and experimental tests, refer to [11].

### 3.1. Main assumptions

The gas turbine plant is simulated at its nominal operating conditions, reported in Table 1. The heat exchangers are supposed to achieve a pinch point of 35 K [6] for the gas–gas exchangers and 20 K for the HRSG.

The air flowrate sent to the catalytic combustor is computed in order to obtain a coefficient of $O_2$ utilization in the cathode equal to 0.7.

The steam flowrate needed to achieve the methane reforming is calculated in order to obtain a water excess of 30% for the following reactions [6]:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

$$H_2O + CO \leftrightarrow CO_2 + H_2 \tag{2}$$

The gas temperature at the cell inlet and outlet are set according to the values achieved in normal operation [7,8], and respecting the following energy balance:

$$m_{\text{in, anode}} h_{\text{in, anode}} + m_{\text{in, cathode}} h_{\text{in, cathode}} = m_{\text{out, anode}} h_{\text{out, anode}} + m_{\text{out, cathode}} h_{\text{out, cathode}} - VI_{\text{out}} - Q_{\text{loss}} \tag{3}$$

where $m$ represents the massflow, $h$ the specific enthalpy, $V$ the cell voltage, $I_{out}$ the electric current provided and $Q_{loss}$ the loss of heat.

The value chosen for the current density is 160 mA/cm$^2$, according to the main known applications and experimental results obtained in the test rig of the University of Perugia [12,14]. The coefficient of fuel utilization is varied by an increase or decrease of the active surface, i.e. varying the number of single cells.

The natural gas flowrate to the gas turbine at the combustion chamber is analytically determined in order to achieve the inlet turbine temperature required (1100 °C).

### 3.2. Simulation results

As stated before, the gas turbine operating parameters do not change in these simulations and they are the ones of Table 1. For this reason, the amount of methane to be supplied to the GT is computed so that the temperature of the gas entering the turbine is 1100 °C. Nevertheless, the values of Table 1 are referred to the normal operation of the GT plant. In the case under study, instead, lower amount of natural gas is burnt (in some cases no gas is needed, therefore the working fluid is only air) and so the output power obtained can be a little different from the one specified by the constructor. In fact the heat needed for the compressed air heating is provided by the MCFC exhaust gases. When the coefficient of fuel utilization is particularly low, the heat produced at the catalytic combustor is high enough to let the bottoming cycle work without additional fuel.

In Fig. 3 it is represented how the plant efficiency varies with respect to cell size and $u_f$. In the figure, only three values of $u_f$ have been plotted. For any value of $u_f$, the plant efficiency is 26.3%, i.e. the gas turbine efficiency, when no power is supplied by the MCFC. When the MCFC power increases, the amount of heat available for the gas turbine increases and so less methane is burnt in the GT combustion chamber (Figs. 4 and 5). If $u_f$ is 0.55 or less (not represented in the graphics because the efficiency obtainable is too low), the minimum flowrate value is zero. After the maximum efficiency is reached, the curve's slope becomes negative; this is due to the fact that not all the heat available at the heat exchanger B can be recycled in the GT cycle, in fact the maximum allowable temperature at the turbine inlet must be 1100 °C. In Figs. 4 and 5 the over plus of heat available at the heat exchanger B together with the relative plant efficiency are represented, for different cell power and $u_f$ equal to 0.6 and 0.7, respectively. As can be noted, the efficiency is affected by the waste heat. This situation is better explained in the following paragraphs.

#### 3.2.1. MCFC size optimization

The present MCFC technology status does not allow to conduct an economic analysis to predict the cost of electricity (CoE) (US$ per kilowatt hour). In fact, while the operating costs (excluding maintenance and service costs) can be predicted through the electric efficiency, the future commercial cost of the MCFC is extremely uncertain.

In this paper it is assumed that the capital cost of MCFC is higher than GT, and so even if the operating cost of the MCFC is lower than the gas turbine one, an acceptable cost of the electricity produced is obtained if the power provided by the MCFC plant section does not exceed 80% of the total power produced.

In Fig. 3 it is possible to note that when $u_f$ is higher than 0.7 the maximum efficiency is obtained when power production of the MCFC is too high compared to the gas turbine. When $u_f$ is lower than 0.6, instead, the total efficiency would be too low. For these reasons, only the cases in which $u_f$ is 0.6 and 0.7 are considered in the following. If $u_f$ is 0.6 the maximum efficiency is obtained for a fuel cell power about four times greater than the gas turbine one. The same efficiency and power ratio can be obtained if $u_f$ is 0.7, in fact in Fig. 3 it is possible to note that the two curves have a common point (designated with the A letter). This means that the same performance can be achieved for two different values of $u_f$. The choice can be made on the basis of the following relation:

$$W_{cell} = VJ_{out}S \tag{4}$$

As stated before, $J_{out}$ is a constant, while $V$ decreases if $u_f$ increases. From Eq. (4), if the same power is obtained by the cell it is preferable to operate with lower $u_f$ because this means a smaller active surface, and so a reduced size and

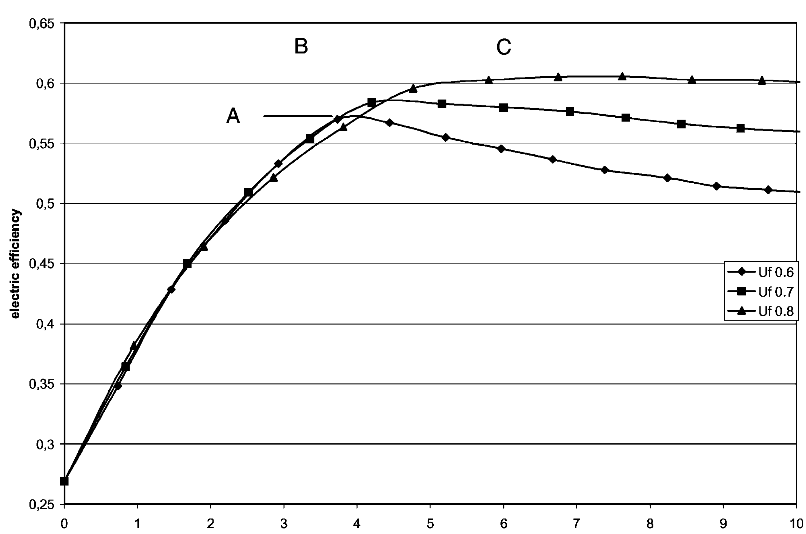


Fig. 3. Plant efficiency comparison.

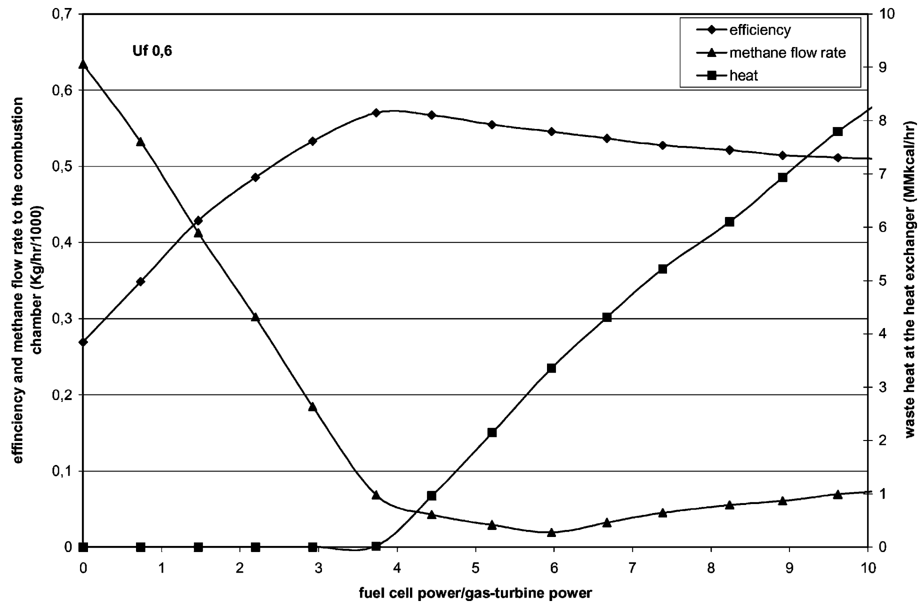


Fig. 4. Efficiency, methane flowrate to the combustion chamber and waste heat, when $u_f = 0.6$.

relative investment cost. For this reason it is preferable to obtain the performance relative to the A point of Fig. 3 with coefficient of fuel utilization equal to 0.6.

In order to fully understand which are the parameters that affect the plant performance and in which way, the efficiency variation has been compared to other parameters variation. In Fig. 4 the electric efficiency is compared with the methane flowrate to the combustion chamber of the gas turbine and with the surplus heat at the heat exchanger A of Fig. 2. The curves of Fig. 4 refer to an $u_f$ value of 0.6, while in Fig. 5 the ones relative to $u_f = 0.7$ are represented. In both the figures it is clear that the plant efficiency increases when the methane flowrate provided to the gas turbine decreases, i.e. when the MCFC power increases thus increasing the cathodic gas flowrate and the relative recycled heat. The efficiency begins to decrease when not all the heat available from the cathodic gas is recycled. This quantity is denoted in the graph with the term "waste heat to heat exchanger".

Finally, how the gas turbine affects the whole plant has been analyzed, comparing the MCFC efficiency to the plant's. These comparisons are represented in Figs. 6 and 7, for $u_f$ equal to 0.6 and 0.7, respectively. The fuel cell efficiency is not affected by its size [6] and so it is possible, with good accuracy, to consider it constant when its size increases. Anyway, it is important to remember that in this

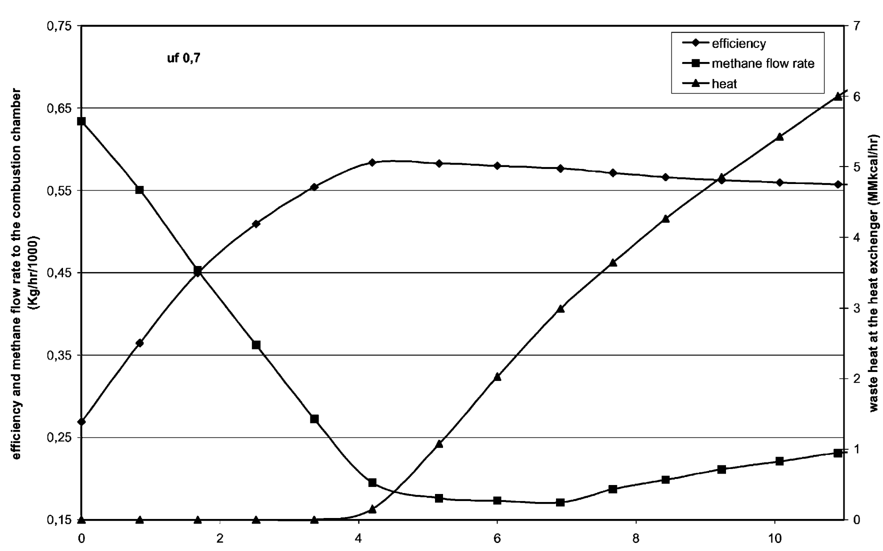


Fig. 5. Efficiency, methane flowrate to the combustion chamber and waste heat, when $u_f = 0.7$.

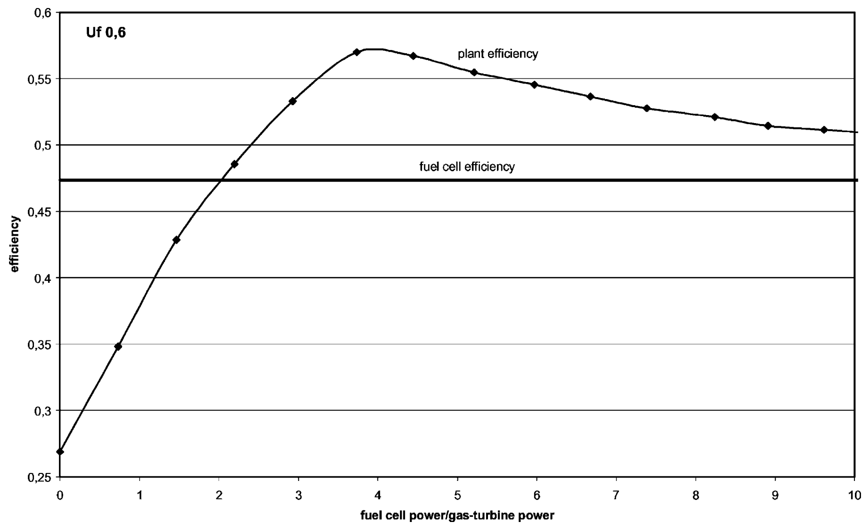


Fig. 6. Influence of MCFC efficiency on plant efficiency ($u_f = 0.6$).

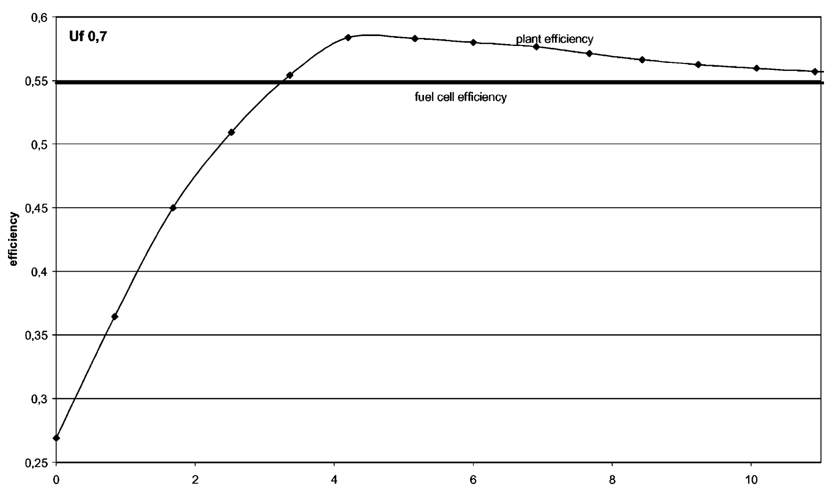


Fig. 7. Influence of MCFC efficiency on plant efficiency ($u_f = 0.7$).

analysis the MCFC power is increased by varying the active surface, i.e. the MCFC size.

If the plant efficiency is equal to the fuel cell one, the resulting operating cost of the plant is the same as that obtained with a stand alone MCFC plant. Having assumed that the capital cost of the gas turbine is lower than the MCFC one, this plant configuration represents remarkable production cost reduction. This cost is much lower for all the plant configurations relative to the graph's points where the plant efficiency is higher than the MCFC one. From a thermodynamic point of view these points represents the only ones where the presence of the bottoming cycle enhances the MCFC efficiency.

### *3.2.2. Operational plant parameters relative to the optimal configurations*

The fuel cell parameters relative to the maximum plant efficiency (points A and B of Fig. 3), for $u_f$ equal to 0.6 and 0.7 are reported in Tables 2 and 3. The plant efficiency relative to these two points are 57 and 58.3%, respectively. The nominal power of each stack is 500 kW. Each stack is composed by 400 single cells, whose active surface is 1 $m^2$.

Fig. 8 reports the temperature profile inside the heat exchanger B of Fig. 1 when $u_f$ is 0.6 and 0.7, respectively.

Table 2
Simulation results for $u_f = 0.6$

| | |
|---|---|
| Fuel utilization | 0.6 |
| Max electric efficiency of the plant (%) | 57.0 |
| Max electric efficiency of the fuel cell (%) | 47.30 |
| Methane flowrate to fuel cell (kg/h) | 1200 |
| Methane flowrate to gas turbine (kg/h) | 68.41 |
| Active surface of single fuel cell ($m^2$) | 1 |
| Number of single FC in a stack | 400 |
| Number of stacks | 16 |
| Fuel cell power/gas turbine power ratio | 3.73 |
| Fuel cell power (kW) | 7576 |

Table 3
Simulation results for $u_f = 0.7$

| | |
|---|---|
| Fuel utilization | 0.7 |
| Max electric efficiency of the plant (%) | 58.3 |
| Max electric efficiency of the fuel cell (%) | 54.80 |
| Methane flowrate to fuel cell (kg/h) | 1440 |
| Methane flowrate to gas turbine (kg/h) | 194.4 |
| Active surface of single fuel cell ($m^2$) | 1 |
| Number of single FC in a stack | 400 |
| Number of stacks | 22 |
| Fuel cell power/gas turbine power ratio | 4.44 |
| Fuel cell power (kW) | 10522 |

As can be observed, the pinch point of 35 K is respected and the compressed air temperature of the gas turbine reaches 1093 and 907.6 °C, respectively, before entering the combustion chamber. Because the gas temperature does not reach 1100 °C needed for the correct operation of the gas turbine, an additional methane flowrate will be needed in the combustion chamber.

### 3.2.3. Further analyses of plant parameters

The analyses of the parameter variation allows to comprehend the influence of the operating factors on the plant

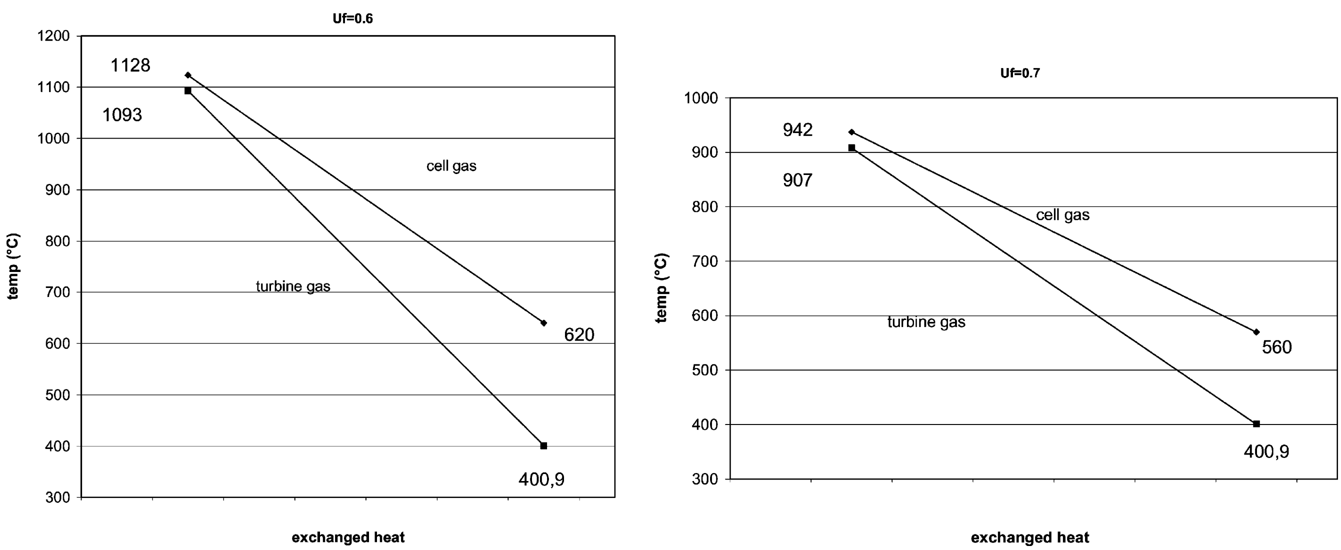


Fig. 8. Temperature distribution in heat exchanger B.

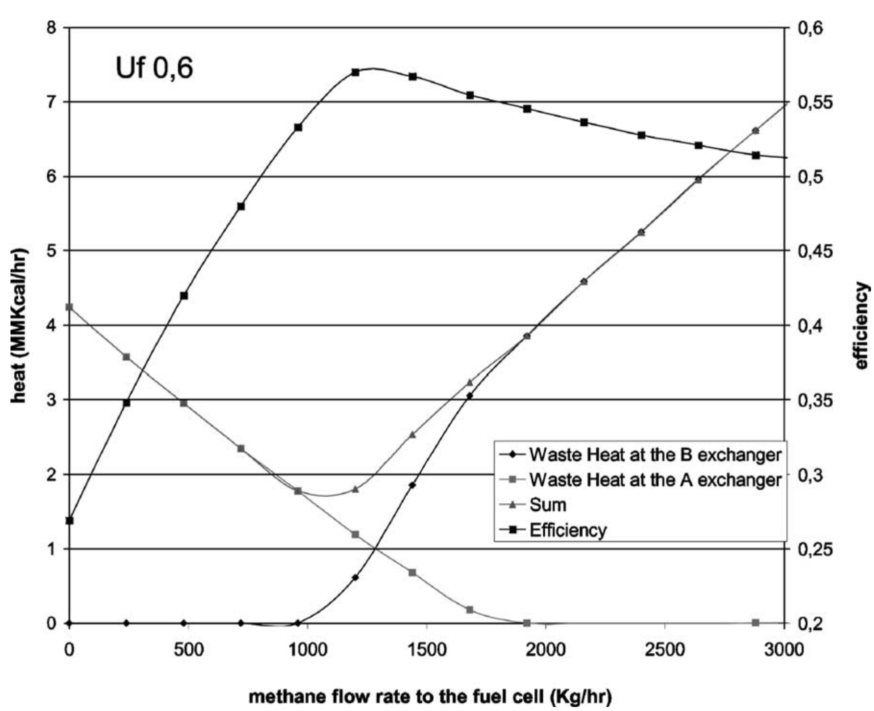


Fig. 9. Efficiency and waste heat.

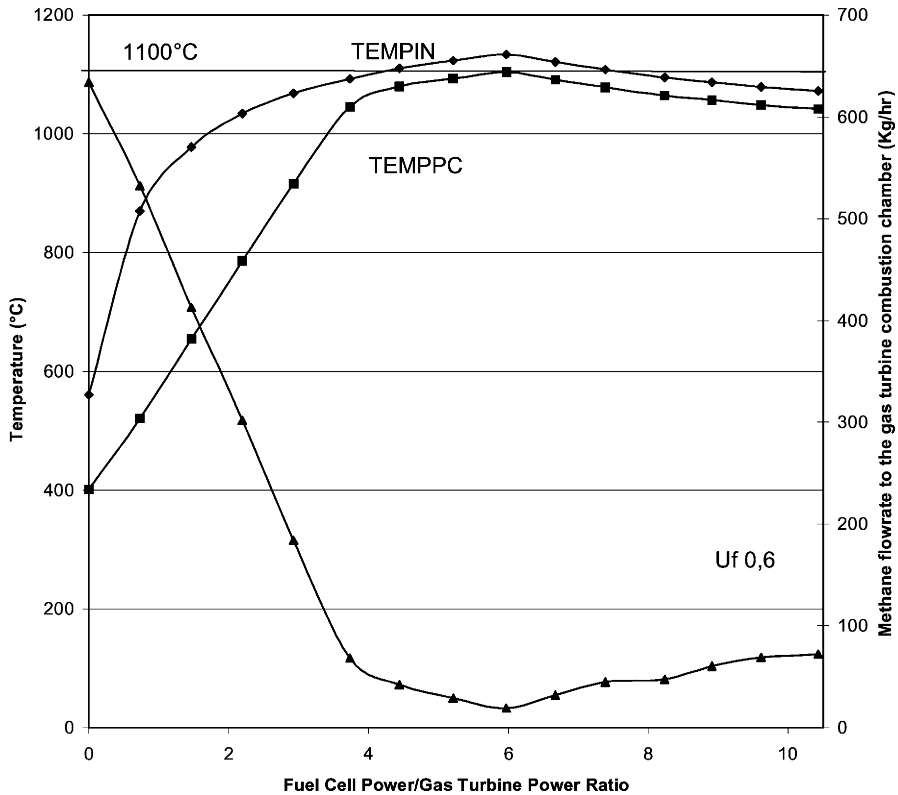


Fig. 10. Temperature vs. methane flowrate to combustion chamber ($u_f = 0.6$).

performance, and so it consents to obtain significant plant enhancement.

The plant efficiency is particularly affected by the amount of waste heat. In fact, varying the fuel cell size, the surplus of heat that cannot be recovered in the heat exchangers is modified. Referring to Fig. 1, the two main heat recovery processes that influence the plant efficiency are the ones that occur in the heat exchanger labeled as A and B. The surplus

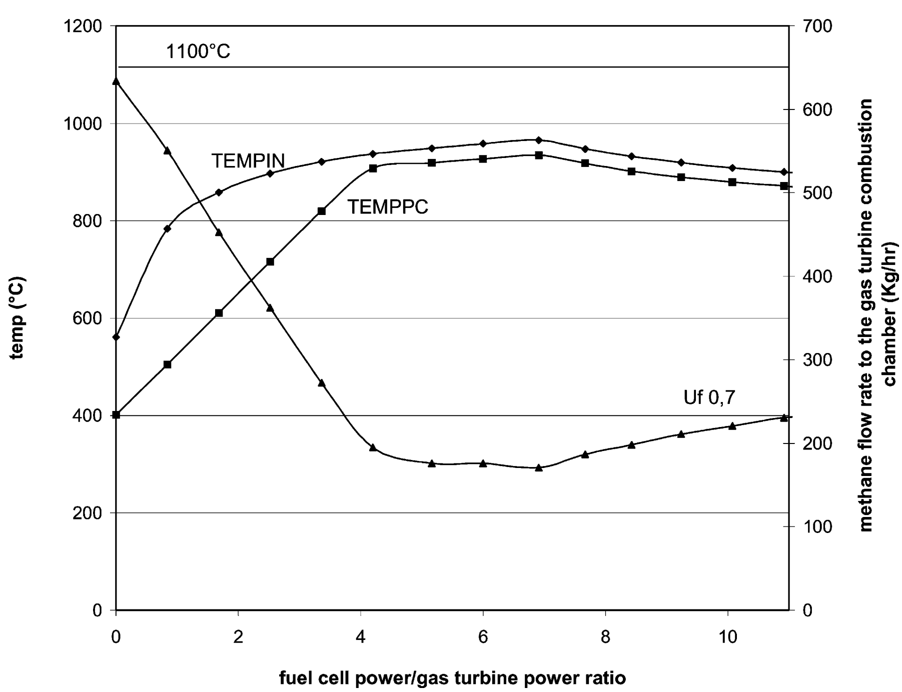


Fig. 11. Temperature vs. methane flowrate to combustion chamber ($u_f = 0.7$).

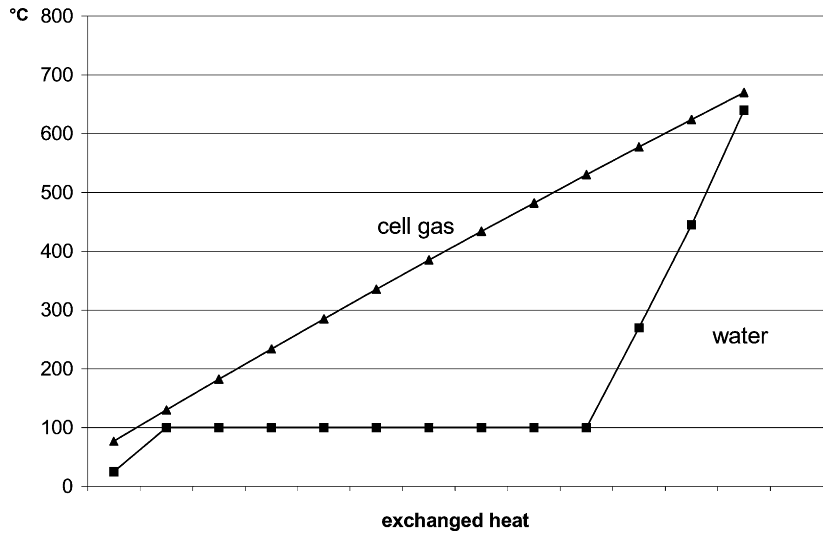


Fig. 12. Temperature in HRSG.

of heat in exchanger B is wasted in exchanger C, while the surplus of A exchanger is released into the atmosphere. Fig. 9 plots these two amounts of heat, their sum, and the electric efficiency when the coefficient of fuel utilization is 0.6. In the *x*-axes, the methane flowrate sent to the fuel cell is plotted; this quantity is proportional to the fuel cell size and it was chosen only for the convenience linked to numerical simulations results. As can be noted, the maximum plant efficiency is obtained when the sum of the waste heat reaches the minimum. The relative graph when the coefficient of fuel utilization is 0.7 is similar to the one of Fig. 10 and so it is not represented in the present work.

A particular meaning for the efficiency is represented by the air temperature in the gas turbine cycle, before entering the combustion chamber. In fact, the higher this temperature, the less the amount of methane demanded by the bottoming cycle in the combustion chamber. In Fig. 10 the temperature of the air exiting heat exchanger B (referring to Fig. 1), when the fuel cell/gas turbine power ration changes is plotted. This temperature is named TEMPPC, while the temperature of the gas from catalytic combustor is labeled as TEMPIN. As can be seen, as TEMPPC increases, the methane flowrate in the combustion chamber decreases, obtaining the minimum when the maximum for TEMPPC is achieved. It must be noted that the maximum value for efficiency is achieved when the waste heat reaches a minimum (as observed in Fig. 9) and not when the methane flowrate is minimum.

In Fig. 11 the same parameters are plotted, but in this case the coefficient of fuel utilization is 0.7. As can be noted, in this case the temperature obtained is about 200 °C below 1100 °C and so a significant amount of methane has to be supplied.

Finally in Fig. 12 the temperature profile of the gas and the water-steam inside the HRSG is represented. Because the cathodic gas exits the fuel cell at about 675–680 °C for each coefficient of fuel utilization and the steam produced is at about 645–650 °C, the graph reported can be considered valid to both situations (i.e. $u_f = 0.6$ and 0.7).

## 4. Conclusion

Today, fuel cells are considered very important devices for future energy conversion. Their high efficiency allow to realize power plants with low pollutant emissions. Moreover, high temperature fuel cells (MCFCs and SOFCs) allow to recycle the heat content of the exhaust gas, in order to realize hybrid power plants. This plant arrangement increases electric efficiency (i.e. reducing the operating plant cost) and at the same time it reduces the investment cost (it is, in fact considered that even in a future scenario capital cost of fuel cells will be higher than the cost of the actual power plants).

In the present work, a parametric performance evaluation of a hybrid MCFC–GT power plant has been carried out. The analysis shows how a cell that is optimized for stand alone operation is not necessarily optimized for the integration in a hybrid cycle. Working with reduced utilization factors, in fact irreversible losses can decrease and do not necessarily yield less electricity production since the heat produced in the post combustor is recovered by the gas turbine section. On the other hand, efficiency higher than 58% can be reached only if new designs of gas turbine are conducted. In fact, the actual commercial gas turbines have to operate with high temperature at the turbine inlet. The high GT operating temperature can be achieved in two ways:

- feeding additional fuel to the combustion chamber of the GT;
- operating with low $u_f$ for the fuel cell.

It has been assessed that while the first solution always leads to a decreasing efficiency, the latter depends on the whole plant configuration.

## References


[1] Draft Reference Document on Best Available Techniques for Large Combustion Plants, European Commission, Technologies for Sustainable Development European IPPC Bureau.

[2] P. Lunghi, S. Ubertini, U. Desideri, Highly efficient electricity generation through a hybrid molten carbonate fuel cell-closed loop gas turbine plant, Energy Conversion Manage. 42 (2001) 1657–1672.

[3] P. Lunghi, S. Ubertini, Efficiency Upgrading of an Ambient Pressure MCFC Plant Through the Introduction of an Indirect Heated Gas Turbine, Turbo Expo, 2001.

[4] S. Ubertini, P. Lunghi, Assessment of an Ambient Pressure MCFC: External Heated GT Hybrid Plant with Steam Injection and Post-Combustion, Fuel Cells, vols. 3–4, Wiley, New York, 2001, pp. 174–180.

[5] P. Lunghi, S. Ubertini, Solid oxide fuel cells and regenerated gas turbines hybrid systems: a feasible solution for future ultra high efficiency power plants, in: Proceedings of the Seventh International Symposium on Solid Oxide Fuel Cells, Tokyo, Japan, 2001.

[6] J.H. Hirchenhofer, et al., Fuel Cell Handbook, fifth ed., vol. 19607, Persons Corporation, Reading, PA, 2000.

[7] C. Haynes, W. Wepfer, Enhancing fuel cell/gas turbine hybrid power system via reduced fuel utilization within indirect internally reforming (IIR) fuel cell stacks, in: Proceedings of the ASME Advanced Energy System Division, AES, vol. 40, 2000.

[8] A. Selimovic, J. Palsson, Networked solid oxide fuel cell stacks with a gas turbine cycle, J. Power Sources 106 (2002) 76–82.

[9] Landfill Gas Cleanup for Cabonate Fuel Cell Power Generation, Department of Energy (DOE) and Electric Power Research Institute (EPRI), 1998.

[10] Post Test Analysis of 20 kW Molten Carbonate Fuel Cell Stack Operated on Coal Gas, Final Report, Department of Energy (DOE) and Energy Research Corporation, ERC, 1996.

[11] P. Lunghi, R. Bove, Reliable Fuel Cell Simulation Through Experimental Driven Numerical Model, Fuel Cells, Wiley, New York, in press.

[12] P. Lunghi, R. Bove, Performance enhancement of fuel cells systems through series and parallel connections of multi stack arrays, in: Proceedings of the IMECE Congress, 2002.

[13] P. Lunghi, R. Burzacca, An effective and reliability method for single fuel cells experimental testing and results comparison: advance control techniques, in: Proceedings of the World Renewable Energy Congress VII and Expo Cologne Congress Centre, Germany, 2002.

[14] B. Bosio, P. Costamagna, F. Parodi, B. Passalacqua, Industrial experience on the development of the molten carbonate fuel cell technology, J. Power Sources 74 (1998) 175–187.