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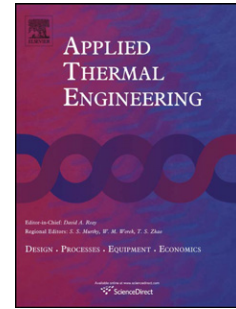
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**Simulation Model of a Molten Carbonate Fuel Cells – Microturbine Hybrid System**

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**Abstract**

A Hybrid System based on High Temperature Fuel Cells coupled to a Microturbine allows a high efficiency, low environmental pollution and it may be exploited as a CHP System producing heat and electricity both Grid Connected and Stand Alone; the overall electrical efficiency could reach a very high value (up to 60 %) and total efficiency could be over 70 % including the contribution due to heat recovery.

In the context of wide research activities of ENEA on High Temperature Fuel Cells and Hybrid Systems – that involve materials, system BoP and fuels – a very great effort has been devoted to design and build, in the ENEA Research Centre of "Casaccia", an experimental Test-Rig based on a Molten Carbonate Fuel Cells Emulator and a Microturbine, to evaluate components performance characteristics at different operating conditions. To obtain a relevant and reliable design data and to compare it to the future experimental test results, a careful numerical simulation analysis of an Hybrid System has been developed by the Authors and it is presented in this Article. The numerical models of the System components were implemented in IPSE Pro™; the performance characteristics have been derived by evaluating operational parameters at nominal and partial loads and, moreover, a sensitivity analysis – varying main working parameters – has been performed on steady state conditions. The simulations show in detail the behaviour of both the Hybrid System and the Subsystems varying the main parameters (output electrical power, inlet flow rates, working pressure, power density, etc.) including rotational speed configuration of Microturbine.

*Keywords:* MCFC; Microturbine, Hybrid System, Simulation, Emulator;

## 1. Introduction

Fuel Cells are electrochemical devices suitable to direct conversion of chemical energy in electricity, with high efficiency and low pollution emissions. Among different Fuel Cells Technologies, High Temperature Fuel Cells (HTFC) operate from 600 °C to 1000 °C with more than 45% of electrical efficiency, also at partial load conditions; even when the contribution of thermal recovery is included the overall efficiency can be over 70 % [1-3].

A pressurized HTFC System allows the direct coupling with a Microturbine ( $\mu$ GT): it is a small gas turbine (some inches of diameter) which can drive an electric generator with a rated capacity of 25-200 kW and net efficiency typically about 25-30 %, rotating at very high speed (about 100000 rpm). Microturbines are very important for a distributed production of electricity and heat because, like HTFC Systems, they may operate on site, allowing also a general reduction of electrical transmission losses [4].

By coupling a Fuel Cell System and a Microturbine we can obtain a new Energy System which presents very high electrical efficiency with a strong reduction of pollution. The performances of an HTFC- $\mu$ GT System is better than a simple HTFC System or a Gas/Steam Turbine Combined System; then, the effect of the high cost of a simple HTFC system can be mitigated and a Hybrid System (HS) can be more competitive, compared to other kinds of power plants. Therefore, the coupling between Microturbines and Fuel Cells is very interesting.

The wide ENEA activity for improvement of new Hybrid Systems based on exploitation of HTFC coupled to a Microturbine includes the thorough evaluation of system performances and the optimization of plant layout through both simulation analysis and reliable experimental tests. An HTFC- $\mu$ GT emulator Test-Rig (named TURBOCELL)

has been designed and built in the “Casaccia” Research Centre in order to investigate on components performance characteristics at different operating conditions and with various types of fuel (mainly to evaluate microexpander performance); the Test-Rig is based on a 500 kW Molten Carbonate Fuel Cells (MCFC) emulator coupled to the Turbec T100 Microturbine and it will be ready for tests in 2011. To obtain relevant and suitable design data for TURBOCELL and to compare experimental results, a careful simulation of an Hybrid System has been developed by the Authors and presented in this Paper; the study is based on an Ansaldo Hybrid System – made up of four MCFC stacks of 125 kW assembled in an original configuration (Twinstack<sup>TM</sup>) [5] – and it has been performed considering a similar subsystem based on a single MCFC stack of 125 kW [6-7].

Some models are available in open literature to study a Hybrid System; references [8-12] are useful for an indirect comparison with our results. The results of this work are reported in tables or graphics and pertain both the optimization and the evaluation of system performance. The numerical simulations show in detail the behaviour of both the Hybrid System and the Subsystems at various operating conditions (design point, sensitivity analysis by varying the main operational parameters, partial load) and they suggest some of the main characteristics of the suitable Microturbine.

## **2. Fuel Cells - Microturbine Hybrid System**

The Hybrid System we have considered consists of the following equipments:

- Fuel Cells Stack;
- Module of Combustion and Reforming;

- Cathodic Blower;
- Heat Exchanger, for internal heat recovery;
- Microgasturbine-Compressor Unit;
- Water-Fuel Treatment Section;
- Steam Generator for the reforming process;
- Heat Exchanger, for external heat recovery;
- Electrical Power Conditioning System.

Stack, Reforming Module and Cathodic Blower compose the Electrochemical Section (ES) which is the heart of the System. The Stack is made up of 150 Molten Carbonate Fuel Cells of  $7,110 \text{ cm}^2$  net section ( $8,100 \text{ cm}^2$  gross surface) which have a rectangular geometry and work at about  $650^\circ\text{C}$  and  $0.35 \text{ MPa}$  [5, 8]. Air and fuel pass through the short side and the long side of the Stack and react to form carbon dioxide and steam; the chemical reactions are generated by contact of air and fuel with Ni-O-based porous cathode and Ni-based porous anode which are separated by an electrolyte consisting of molten carbonates in an inert matrix. The MCFC should feed a fuel gas containing hydrogen and carbon monoxide which acts by fuel and it allows the chemical reactions; currently a suitable fuel can be obtained using a reforming process from methane or biogas [1-3].

The Reformer and the Catalytic Burner are coupled in an original compact configuration (here named MCR) with an integrated counter-current Heat Exchanger, where the chemical reactors are together in just one equipment which has the internal separation surface as a thermal exchange wall to minimize thermal dissipation [5, 8].

The methane conversion takes place with the following main typical features of both internal and external reforming:

- independence between reformer and fuel cells life;
- absence of catalyst deactivation problems;
- wide flexibility of operation;
- simple structure and maintenance;
- reduction of heat losses;
- possibility to build standard units.

The purpose of gas combustion is:

- to remove fuel in the anodic flow outgoing from the stack;
- to attain an optimum process temperature in both anodic and cathodic side;
- to allow the right operating conditions of the Stack;
- to obtain the carbon dioxide required to Stack electrochemical reactions.

At first, after a clean-up treatment, steam and natural gas are mixed and the product syngas moves to a Preheater Heat Exchanger in which a part of thermal energy of inlet anodic gas is carried away. The hydrogen-rich gas crosses the anodic side of Cells and reacts with the oxidizing gas of cathode and the electrical energy is produced by direct conversion; the exhaust anodic gas mixed with a part of cathodic exhaust gas (about 65-70% of exhaust cathodic gas is recycled) move inside the Catalytic Burner. The exhaust gas coming out from Catalytic Burner is mixed with atmospheric air before the inlet to cathode. The process flow sheet pertaining the inlet gas is shown in Figure 1.

Downstream of the electrochemical device exhaust gas moves through a Microturbine; it produces further electricity and medium temperature heat which can be recovered and used inside the same process or in other applications. A simple block diagram is shown in Figure 2.



### 3. Modelling of system components

The Hybrid System has been implemented by using IPSE Pro™ version 3.1; this software works on Windows™ platform and it is very useful for many simulations of thermo-chemical processes. The software includes two main subroutines – MDK and PSE – which are integrated in the code by special algorithms to minimize the computational time. In MDK (Model Development Kit) we can modify the model libraries to create new equipment, developing numerical models in MDL (Model Development Language). MDK allows the direct conversion of MDL instructions into PSE compatible code. PSE (Process Simulator Environment) is a part of the software dedicated to build a system flow sheet and to set up parameters to run simulations.

The MCFC and MCR models were not available in the equipments library. These were built in MDL language; turbomachinery, heat exchangers and other plant components have been simulated by predefined blocks. To obtain a light and suitable code, some approximations have been introduced and a one-dimensional design approach has been adopted; this method has been very useful and fast to derive the operative variables and to predict the best working conditions of single components, considering the high complexity of the system.

A preliminary study of the simulation models were done to show the appropriateness of the approximation degree (it was not worth doing a deeper analysis in relation to the main goals of this work).

The results of whole modelling activity have been compared to the available results in quoted references, in particular reference [8] which deals with Hybrid System modelling based on AFCo “Serie 500” Power System.

### 3.1. Electrochemical Section

The building of the Electrochemical Section model starts with the definition of the single models:

- 125 kW Stack;
- MCR.

The appropriate design features of MCFC stack and MCR are very difficult to translate in analytic IPSE Pro code, due to many variables to be considered in the simulation of the system (mostly at partial load condition). The main assumptions to build the ES models are:

- steady state conditions;
- adiabatic conditions (vessel insulated by low conducting materials) [8];
- gaseous products and reactants have a behaviour like an ideal gas;
- carbon deposition effects are negligible [8];
- poisoning of catalyst absent;
- pressure losses considered are derived by literature data [3, 5, 8];

To find solutions we need to solve three sets of equations:

- mass balance (for each gas component);
- energy balance;
- local kinetics of the chemical reactions.

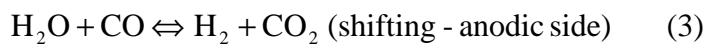
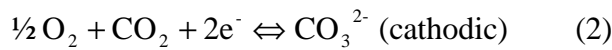
All reactions have to be considered as occurring at the equilibrium temperature.

#### 3.1.1. MCFC stack

The stack modelling requires other assumptions:

- all Cells have the same behaviour;
- thermal exchange between stack cells is absent;
- both contact and polarisation resistances are negligible.

Fuel cells reactions are the following:



The previous reactions 1 and 2 regard the half-reactions which take place in the porous electrodes. The overall reaction is exothermic: one mole of hydrogen reacts with half mole of oxygen producing one mole of high-temperature steam and electricity. The last reaction increases the hydrogen flow moving through the stack.

An empirical equation is necessary to close the single model simulation [3]:

$$K_{shift} = e^{\left(\frac{4276}{T} - 3.961\right)} \quad (4)$$

As hypothesized above, Fuel Cells internal resistance is an ohmic resistance, so the real voltage has been estimated by means of Ohm's law:

$$V = E - R \cdot J \cdot A \quad (5)$$

where  $E$  is the ideal voltage [V] estimated by Nernst's equation,  $J$  is the current density [mA cm<sup>-2</sup>] and  $A$  is the overall area of cells surface [cm<sup>2</sup>].

Nernst's equation describes the potential, at the equilibrium, in terms of partial pressures or molar fractions respectively:

$$E = E_0 + \frac{RT}{2F} \cdot \ln \frac{P_{\text{H}_2,an} \cdot P_{\text{CO}_2,cat} \cdot P_{\text{O}_2,cat}^{1/2}}{P_{\text{H}_2\text{O},an} \cdot P_{\text{CO}_2,an}} \quad (6)$$

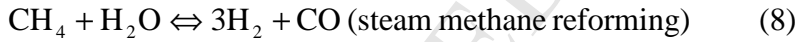
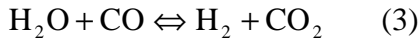
$$E = E_0 + \frac{RT}{2F} \cdot \ln \left( \left( \frac{p}{n_{tot\_cat}} \right)^{1/2} \cdot \frac{n_{tot\_an}}{n_{tot\_cat}} \right) + \frac{RT}{2F} \cdot \ln \left( \frac{n_{H_2,an} \cdot n_{CO_2,cat} \cdot n_{O_2,cat}^{1/2}}{n_{H_2O,an} \cdot n_{CO_2,an}} \right) \quad (7)$$

For a single cell, real voltage behaviour (V) was determined depending on the fuel utilization factor (FU) (Fig. 3) and was also derived by varying cell current density (Fig. 4), following literature data. [2-3].

### 3.1.2. MCR

The reforming module has also been simplified: the process of combustion ideally takes place inside a combustion region which is small compared to the MCR itself. Then, the reference temperature considered (warm flow temperature) for the heat exchange is the maximum temperature in the combustion process.

Reforming reactions are steam-methane reforming and water-gas shift:



and equations 4 and 9 are needed to calculate the constant of equilibrium and for the closure of the model [3, 14]:

$$\log K_{ref} = AT^4 + BT^3 + CT^2 + DT + E \quad (9)$$

For the MCR model we have simulated the steam methane reforming in one side, combustion of reactants in the other side and the energy transmission through the thermal exchange wall. In the combustion side  $H_2$ ,  $CH_4$  and  $CO$  was fully burned ( $x$ ,  $y$  and  $z$  are the molar flow rate, respectively). The link between reformer and combustion sides is represented by the energy equations:

$$m_{in,CB} \cdot h_{in} + q_{react_1} \cdot x + q_{react_2} \cdot y + q_{react_3} \cdot z - q_{trans} = m_{out,CB} \cdot h_{out} \quad (10)$$

$$m_{in,SMR} \cdot h_{in} - q_{react_{ref}} \cdot x' + q_{react_{shift}} \cdot y' + q_{trans} = m_{out,SMR} \cdot h_{out} \quad (11)$$

where  $m$  is the mass flow rate,  $h$  is the enthalpy,  $q_{react}$  is the enthalpy of reaction,  $q_{trans}$  is the thermal energy exchanged in the MCR internal wall and where  $x'$  is the molar flow rate of  $\text{CH}_4$  which reacts producing hydrogen and  $y'$  is the molar flow rate of  $\text{CO}$  produced with steam methane reforming.

The flow conceptual diagram of MCR shows the integration of reforming and combustion side in the overall model [Fig. 5].

Reforming and shifting dependence on thermal power exchanged in the reforming module are reported in Figure 6. Conversion process efficiency increases as well as the heat power trend, while at the same time, shifting efficiency decreases.

#### 4. Simulations at nominal load

At rated load conditions, two simulations have been proposed: in the first simulation the system has been considered as having negligible pressure drops (Case 0). In the second one, we have considered pressure drops (Case 1). Inlet flow rates and their mass flow compositions are scheduled in Table 1.

To start the simulation, we need other data specifications [5, 8]:

- fuel utilisation factor;
- working pressure;
- anodic and cathodic mass flow rate.

In the Case 1, pressure drops in MCR and Stack have been considered 2% (7 kPa) of working pressure (0.35 MPa), by each side [5].

At last, some input assumptions have been made pertaining efficiencies of:

- Cathodic Blower;

- air and fuel Compressor and their Electrical Motors;
- Electrical Power Conversion System;

based on literature data [3, 10, 12].

Unlike reference [9] stack efficiency is defined as the ratio of output electric power coming out by the stack and the lower heating value (LHV) of the inlet fuel supplied to the system:

$$eff_{stack} [\%] = \frac{P_{stack}}{\sum (m_{i,in} \cdot H_i)} \cdot 100 \quad (12)$$

Electrochemical System efficiency and Hybrid System efficiency are:

$$eff_{ES} [\%] = \frac{P_{stack} - P_{blow}}{\sum (m_{i,in} \cdot H_i)} \cdot 100 \quad (13)$$

$$eff_{HS} [\%] = \frac{P_{stack} + P_{\mu GT(net)} - P_{blow} - P_{fuel}}{\sum (m_{i,in} \cdot H_i)} \cdot 100 \quad (14)$$

$P_{\mu GT(net)}$  is the net power produced by Microturbine/Air-Compressor Unit.

In Table 3 main results of Case 0 and Case 1 are reported and they can be compared with [8]. Figure 7 shows the Hybrid System flow sheet; the stream compositions in Case 1 are shown in Table 4.

The grade of methane conversion is not too high: reforming temperature should be up to 800°C to obtain higher conversion [8]. Higher temperatures aren't possible in a MCFC based Hybrid System when the Fuel Cells System is at the upper cycle: so, the low inlet microturbine temperature (about 650°C) depends on the MCFC operating temperature. However, the temperature of exhaust gas flow coming out from the Microturbine outlet is about 450°C and it is still useful for both steam and heat production; this one improves the system global efficiency.

The differences between the simulations “Case 0” and “Case 1” show the influence of

pressure drops; reforming temperature depends on the work pressure and also on heat exchanged. It results by simulation analysis that energy losses are mainly due to pressure losses.

## 5. Sensitivity analysis

The purpose of the sensitivity analysis is to establish the dependence between the main characteristic system parameters and the following ones:

- fuel utilisation;
- current density;
- operating pressure;
- air flow rate;
- steam/methane ratio;
- efficiencies of turbo-expanders, electrical motors and electrical power conditioning system.

The fuel consumption can be accounted in the model by means of the following parameters:

$$FU = \frac{n_{H_2,in} - n_{H_2,out}}{n_{H_2,in}} \quad (15)$$

$$FU^* = \frac{x + y}{n_{H_2,in} + n_{CO_{in}}} \quad (16)$$

$$OU^* = OU_{O_2} + OU_{CO_2} \quad (17)$$

$$n_{O_2} \cdot \frac{OU_{ox}}{100} = \frac{x + y}{2} \quad (18)$$

$$n_{CO_2} \cdot \frac{OU_{diox}}{100} = x + y \quad (19)$$

where:

$FU$  is the fuel utilisation parameter;

$FU^*$  is the corrected fuel utilisation parameter;

$OU^*$  is the overall oxidant utilisation parameter;

$OU_{O_2}$  is the oxygen utilisation parameter;

$OU_{CO_2}$  is the carbon dioxide utilisation parameter.

$n_{X,in}$  and  $n_{X,out}$  are respectively the molar flow rate of species entering and leaving the fuel cell system,  $x$  is the molar flow rate of hydrogen reacting in the fuel cell and  $y$  is the molar flow rate of carbon monoxide reacting in the anodic side (shifting).

Another useful parameter is the steam reforming factor:

$$RF_{st.ref} = \frac{n_{CH_4,in} - n_{CH_4,out}}{n_{CH_4,in}} \quad (20)$$

which accounts for the steam reforming reaction; the balance of molar flow rates in the reformer is the following:

$$n_{H_2} = n_{H_2,in} + 3 \cdot x' + y' \quad (21)$$

where  $x'$  and  $y'$  are respectively the molar flow rate of  $CH_4$  which reacts producing hydrogen and the molar flow rate of  $CO$  produced with steam methane reforming.

### 5.1. Fuel utilisation

According to references, an increase of  $FU$  (from 65% to 85%) slightly rises the stack operating mean temperature (from about 630°C to 660°C), at the same time it lowers the steam reforming parameter, as the fuel coming in the MCR combustion region diminishes. More hydrogen reacts into the stack but the available energy with a greater



FU is slightly less than energy loss into successive combustion process. Due to a FU increase, there is, also, an increase of the oxidant utilisation parameter  $OU^*$  and a decrease of carbon dioxide emission from the Hybrid System. Efficiency of the HS diminishes from 59.3% to 57%.

### 5.2. Current density

An increase of the operating current carries out a low decrease of cell operating voltage due to electric losses, which mainly depend on current density  $J$  from equation 5. At the same time, when  $J$  increases, also HS power shows a significantly increase from 129.2 kW to 141.6 kW and the HS efficiency rises from 55.6% to 60.9% (Fig. 8). Therefore, under assumptions made in this work, changes in current density increases the whole HS efficiency.

### 5.3. Working pressure

Table 5 shows the dependence between the HS performance and the working pressure variation at fixed current density. The increase of the working pressure has remarkable results on the performance of the Bottoming Cycle, where efficiency increases with increasing pressure (it is 10.9% at 2.5 bar and 17.0% at 5 bar). According to References [3, 8], the same type of results are in the Electrochemical Section where the efficiency rises from 45.4% to 52.6%, due to the increased activity of reagent gases.

The Hybrid System electric efficiency can reach over 60% when operating pressure is 5 bar. When pressure increases, the operating voltage increases too; meanwhile, as a secondary effect, the reforming is worsened because chemical equilibrium is shifted to the reactants.

#### 5.4. Air flow rate

The flow rate of external air can reach 90% of the whole air flow rate circulating in the stack. Working with a flow rate of fresh air less than the rated value, the mean temperature in the stack reaches a value near 700°C. A reduction of fresh air up to 85% is possible by varying the flow rate of recycled gas. In this case, the operating temperature has a suitable value for the stack operation. The system efficiency and the steam reforming parameter increase.

Table 6 shows results obtained by a numerical simulation with the air flow rate sensitivity analysis by modifying the cathodic recycle rate.

#### 5.5. Steam methane ratio

Results obtained by steam methane ratio sensitivity analysis show the ES efficiency reduction for high rate while the efficiency of Hybrid System has a slight increase because more fuel burns in the Burner and more high-temperature steam is generated. The increase of the input steam improves the fuel reforming but it doesn't improve the chemical reactions in the fuel cells. In any case, the ratio between vapour and methane values must be over 3 in order to avoid the deposit of carbon [1, 8-9]. Results are shown in Table 7.

#### 5.6. Efficiency of components

In the numerical simulation, the following parameters have been introduced by means of a set of given values:

- flow rate: fuel, steam and air;

- fuel utilisation factor;
- recycled gas flow;
- efficiency of turbomachines;
- efficiency of electric motors;
- efficiency of power conditioning system.

The variation of compressor efficiency external to the Electrochemical Unit modifies the thermodynamic conditions of gas involved in the process. In the numerical simulation for the fuel cell stack, a given value of FU and J has been assigned and the results show negligible consequences on the overall efficiency. The error due to compressor efficiency is negligible because it is less than 2%.

The variations of efficiencies of electric machines and of the power conditioning system affect the output power generated by the whole system but the variation of the generated power is due nearly entirely to the motor driving the air compressor (which is external to ES). In the worst case, the error in the estimate of the Hybrid System efficiency can reach 9%.

## **6. Hybrid system simulation at partial load**

In a conventional system for power generation operating with a gas turbine we can vary the output power generated, maintaining a constant air flow rate and varying the fuel rate feeding the combustion chamber. The management of a Hybrid System is difficult as it is to have an optimum operating temperature of the anodic and the cathodic process streams in the Stack: the inlet temperature should be not less than 580°C. Moreover, the cathodic stream at inlet should have a content of oxygen and carbon dioxide not less

than a 10% and a 5% respectively: note that this condition shouldn't occur by keeping a constant air flow rate.

In the numerical simulation, the condition at partial load was stated by varying proportionally the flow rate of inlet gases in relation to a given output power. The reference value is the power generated by the electrochemical unit. The FU was maintained at a value of 75% while the change of thermochemical conditions, due to a variation of flow rates of feed gases, hasn't been considered. During the numerical simulation process, the output power of electrochemical section was reduced in each set of run by 10%, starting from 100% of load, in the range 100÷50%.

When a fixed or variable speed Microturbine is adopted, the obtained results are reported in Figures 9 and 10 respectively and show that HS efficiency is highly affected by the type of Microturbine installed. In particular, Figure 10 shows the strong performance reduction at partial loads when the rotational speed is fixed; in this case the reduction of the HS efficiency can reach up to 10%.

## **7. Conclusions**

The paper deals with a Molten Carbonate Fuel Cells - Microturbine Hybrid System simulation, in the context of a wide research activity of ENEA on HTFC Systems; a numerical model has been implemented by using IPSE Pro 3.1 and detailed simulations have been conducted to provide a reliable analysis in order to evaluate the system performance.

Each single model of devices and the whole system were duly validated by comparing literature data; the reliability of the whole simulation code has been validated also

making a thorough sensitivity analysis. The behaviour of the components and of the HS shown by the numerical simulations is in accordance to the quoted papers; therefore, appropriate simplifications were introduced and moreover, in this work, cells electric resistance are well approximated with Ohm's law.

The steady state simulation of the Hybrid System shown that the efficiency both of the Electrochemical Unit and of the whole Hybrid System can be higher than that of gas-steam turbine conventional power plant. Indeed, at nominal load, the HS yield is about 135 kW of electric power (22 kW from Bottoming Cycle) while about 100 kW are available as thermal power and they can be recovered by thermal cogeneration; finally, the rate between the output electric energy and the inlet chemical energy of fuel is close to 60%. This result is well shared in literature and it is very interesting in relation to a possible commercial development of such CHP systems for distributed generation of electricity and heat. The result is also considerable for the choice of the Microturbine and it is also very important for the study of Microturbine by Emulator. Moreover, the simulation shows that pressure losses into reactors and into the piping must be minimized as much as possible.

The sensitivity analysis of characteristic parameters shows that:

- marked efficiency increases can be reached just by increasing the operative pressure since it doesn't just increase the ES efficiency but also the Bottoming Cycle; on the other hand, at higher pressure the chemical equilibrium of the reforming reaction tends to move toward the reagents;
- the efficiency of electric machines affect the output parameters in a remarkable measure; it is due nearly entirely to the motor driving the air compressor, whereas the efficiency of the recirculation blower affects the power output and the efficiency

- of the whole system only slightly;
- increase on efficiency can be given by the simultaneous modification of the quantity of recycled exhaust and of the air introduced. The reduction of inlet air and the increase of the recycled gas gives back an increase of carbon dioxide partial pressure and it improves the cathode performance of MCFC. However, the particular configuration of the HS doesn't allow a wide regulation of the recycle without inlet flow rates modifications because we would have an increase in stack operating temperatures and the obtained profit about the global output would be very small;
  - positive effects are also obtained by increasing the current density but we should consider all the electrical losses to avoid low stack voltage;
  - values of steam/methane ratio greater than 3.5 doesn't increase the overall efficiency of the system and moreover the cell reactions are worse;
  - 75% of FU ratio makes a good balance between Topping Cycle and Bottoming Cycle.

The analysis at partial load shows that:

- the choice of a Microturbine with variable turn speed should be better because the reached efficiency is almost constant;
- both Stack and ES efficiencies are always almost constant (this is a peculiar feature of real Fuel Cells Systems);

The HS partialisation can also be obtained thanks to a by-pass, which can allow the shifting of a part of fuel contained into the anodic inlet stream direct to a Post-Burner (which will have the aim to increase the temperature of the inlet microturbine flow).

The coupling of a MCFCs and Microturbine is very useful, both for an increase of

output power generated and for the System efficiency. Moreover, the numerical simulation allows to define the optimum configuration of system and to derive also the process parameters of the gas stream when moving through the Stack and the Microturbine. Finally, the low level of CO<sub>2</sub> emission (Table 4) should be positive to a deeper examination on the potentialities for the diffusion of this technology.

The results reached by this work will be useful for running the experimental platform built inside the “Casaccia” Research Centre of ENEA.

Meanwhile, the Authors are studying the possibilities and the advantages of more accurate models, by eliminating of some simplifications.

A work on the improvement of the plant process is under way, to achieve even higher conversion outputs.

Further investigations starting from the obtained results by the Test-Rig will be carried out to optimize the running parameters.

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**Acronyms**

ES	Electrochemical Section
HS	Hybrid System
HTFC	High Temperature Fuel Cells
MCFC	Molten Carbonate Fuel Cell
MCR	Module of Combustion and Reforming
MDK	Model Development Kit
MDL	Model Development Language
PSE	Process Simulator Environment
$\mu$ GT	Micro-Gas Turbine

**Nomenclature**

A	Overall area of cells surface
E	Ideal voltage
$E_0$	Ideal voltage at standard temperature and pressure
eff	Efficiency of device
F	Faraday constant
FU	Fuel utilization parameter
h	Enthalpy
J	Current density
$K_{ref}$	Reforming reaction rate constant
$K_{shift}$	Shift reaction rate constant
M	Mass flow rate

n	Molar flow rate
OU	Oxidant utilization
P	Power
p	Pressure
q <sub>react</sub>	Enthalpy of reaction
q <sub>trans</sub>	Thermal energy exchanged by the MCR internal wall
R	Ohmic resistance
R	Universal gas constant
RF	Reforming parameter
T	Temperature
V	Real voltage

*Subscripts*

an	Anode
cat	Cathode
CB	MCR Catalytic Burner
in	Inlet
out	Outlet
ref	Reforming reaction
shift	Shifting reaction
SMR	MCR reformer
tot	Total

- Fig. 1. Enrichment treatment of inlet gas.
- Fig. 2. Simplified block diagram of an Hybrid System.
- Fig. 3. Cell voltage vs fuel utilization.
- Fig. 4. Cell voltage vs current density.
- Fig. 5. Interaction between Reformer and Burner in the MCR model.
- Fig. 6. Reforming-shifting conversion parameters vs thermal power.
- Fig. 7. Flow sheet of the Hybrid System.
- Fig. 8. Effect of current density on Stack voltage; Hybrid System overall power.
- Fig. 9. Efficiency at partial loads (microturbine configuration: variable rotation speed).
- Fig. 10. Efficiency at partial loads (microturbine configuration: constant rotation speed).

- > performance of mcf<sub>c</sub>- $\mu$ gt hybrid system have been evaluated by numerical simulations
- > simulations at design point, partial loads and sensitivity analysis varying main parameters
- > electrical efficiency could reach 60 % and could be over including the contribution due to heat recovery
- > increase of efficiency can be reached by increasing the operative pressure and the current density
- > 75% of FU ratio allows a good balance of performance between topping cycle and bottoming cycle
- > microturbines with a variable turn speed allow to reach an almost-constant efficiency

Table 1. Inlet flow rates and compositions.

	Mass flow rate [kg h <sup>-1</sup> ]	Temperature [°C]	Molar fraction [%]	Formula
Air	620	25	79/21	N <sub>2</sub> , O <sub>2</sub>
Methane	17.4	25	89.7/6.2/4.1	CH <sub>4</sub> , H <sub>2</sub> , H <sub>2</sub> O
Steam	60.6	170	100	H <sub>2</sub> O

Table 2. Operating specifications and efficiency of devices.

Operating parameters		
Fuel utilisation	75	%
Current density	155	mA cm <sup>-2</sup>
Anodic mass flow	78	kg h <sup>-1</sup>
Cathodic mass flow	3500	kg h <sup>-1</sup>
Plant pressure	0.35	MPa
Pressure drop	0.07	MPa
Device	efficiency [%]	
Air and fuel compressor	85	
Electrical motors	90	
Electrical power conditioning system	96	

Table 3. Operating results.

<i>Devices</i>	Case 0	Case 1
	Power [kWe]	
Stack	125.8	126.4
Electrochemical section	125.8	114.7
Bottoming cycle	21.0	22.3
Hybrid system	145.3	135.5
Reformer [kW <sub>r</sub> ]	73.1	73.1
To external exchanger [kW <sub>r</sub> ]	91.3	100.3
	Efficiency [%]	
Stack	56.3	56.6
Electrochemical section	54.1	49.3
Microturbine	15.4	14.8
Hybrid system	62.5	58.2
Reforming module	84.8	85.1
	Temperature [°C]	
Stack (anodic flow)	610	609
Stack (cathodic flow)	608	611
Stack (exit)	641	644
Reformer (exit)	700	702
	Other parameters	
Oxidant utilisation [%]	26.8	27.1
Cell voltage [V]	0.793	0.796
Cathodic recycle [%]	81.2	79.2
Steam/methane ratio	3.48	3.48



Table 4. Inlet chemical compositions (Case 1).

<i>Stream</i>	<i>O<sub>2</sub></i>	<i>CO<sub>2</sub></i>	<i>H<sub>2</sub>O</i>	<i>N<sub>2</sub></i>	<i>H<sub>2</sub></i>	<i>CO</i>	<i>CH<sub>4</sub></i>
Cathode	11.4	5.9	20.7	62.0	0	0	0
Anode	0	6.7	33.1	0	50.5	6.2	3.4
Microturbine	9.9	3.8	24.3	62.0	0	0	0

Table 5. Pressure sensitivity analysis.

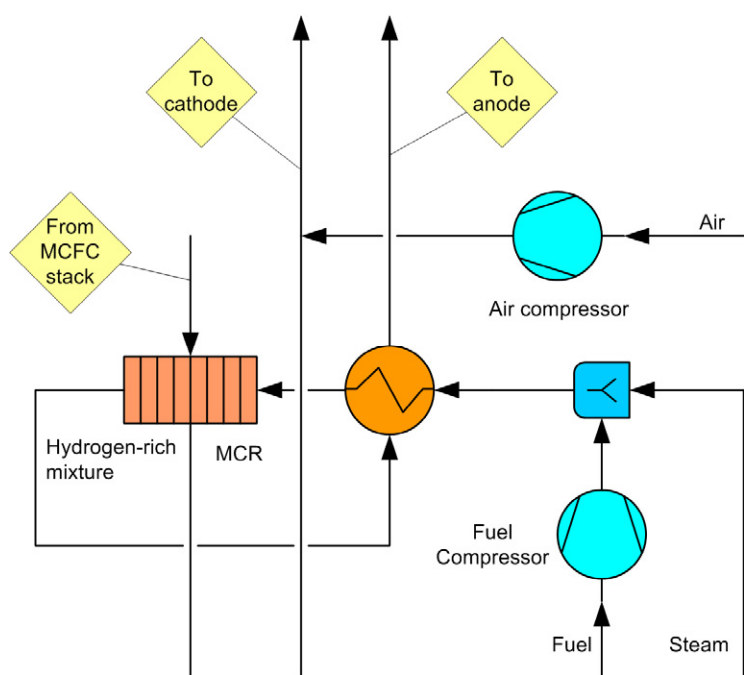
<i>Working pressure [bar]</i>	2.5	3.5	5
Oxidant utilisation [%]	27.4	27.1	27.0
Cell voltage [V]	0.768	0.796	0.823
Conversion parameter [%]	86.4	85.1	84.4
ES efficiency [%]	45.4	49.3	52.6
HS efficiency [%]	52.4	58.2	63.0
ES power [kW]	105.6	114.7	122.3
HS power [kW]	121.8	135.5	146.6
Stack outlet temperature [°C]	637	645	652

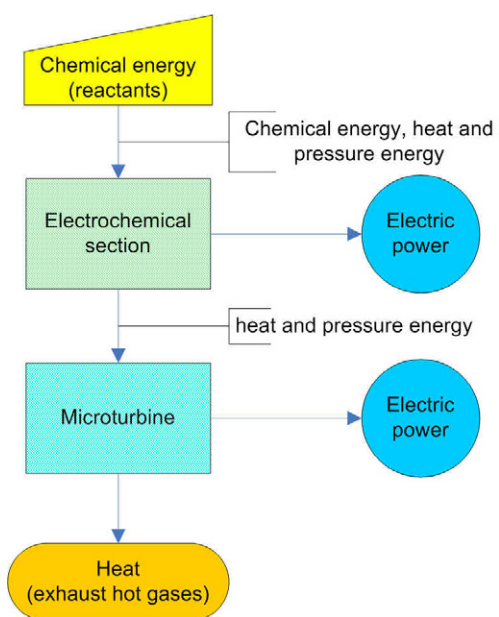
Table 6. Air flow rate / recycled gas flow rate sensitivity analysis.

<i>Air flow rate [%]</i>	<i>85</i>	<i>90</i>	<i>95</i>	<i>100</i>
Oxidant utilisation [%]	49.3	40.0	32.8	27.1
Cell voltage [V]	0.775	0.784	0.791	0.796
ES efficiency [%]	50.8	50.6	50.1	49.3
HS efficiency [%]	59.7	59.5	59.0	58.2
HS power [kW]	139.0	138.4	137.2	135.5
Stack outlet temperature [°C]	691	671	656	644
Conversion parameter [%]	90.4	88.4	86.5	85.1
Cathodic Recycle [%]	59.6	68.3	74.5	79.2

Table 7. Steam / methane ratio sensitivity analysis.

<i>Steam/methane ratio</i>	<i>3.0</i>	<i>3.5</i>	<i>4.0</i>	<i>4.5</i>	<i>5.0</i>
Cell voltage [V]	0.799	0.796	0.793	0.790	0.766
HS power [kW]	134.9	135.5	135.6	135.8	135.8
HS efficiency [%]	58.0	58.2	58.3	58.4	58.4
Stack outlet temperature [°C]	642	644	659	678	702
Conversion parameter [%]	78.4	85.1	86.8	87.1	87.4
Recycle [%]	79.5	79.2	78.9	78.7	78.3





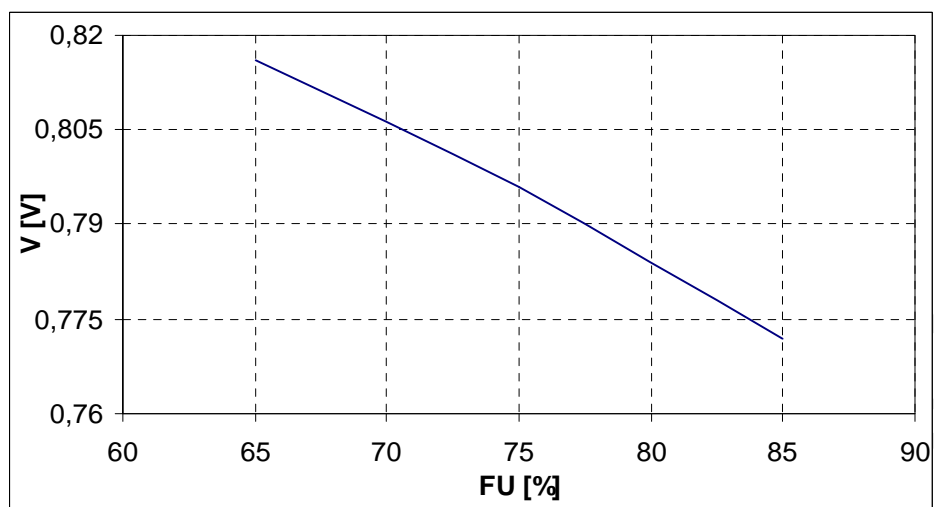


Fig. 3

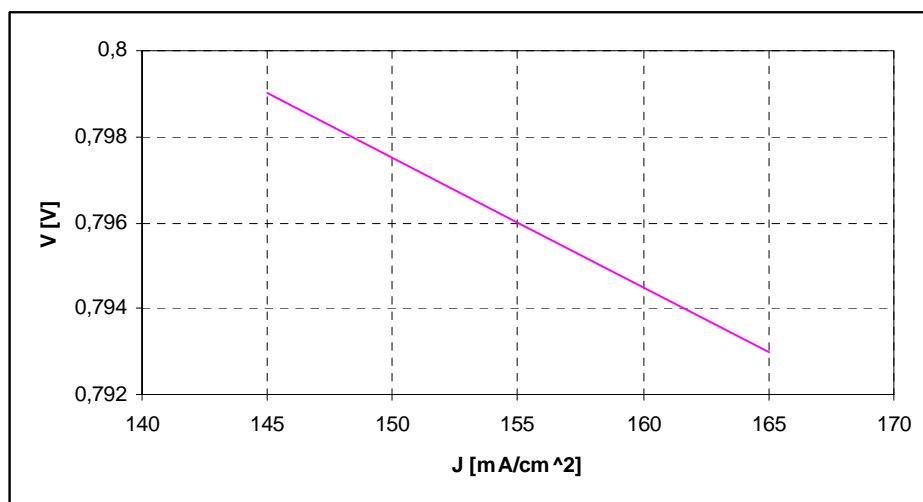
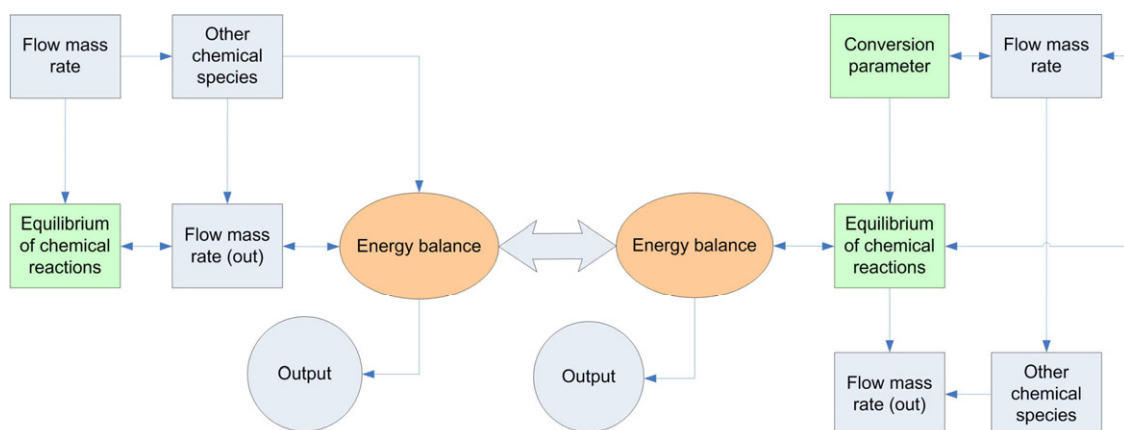


Fig. 4





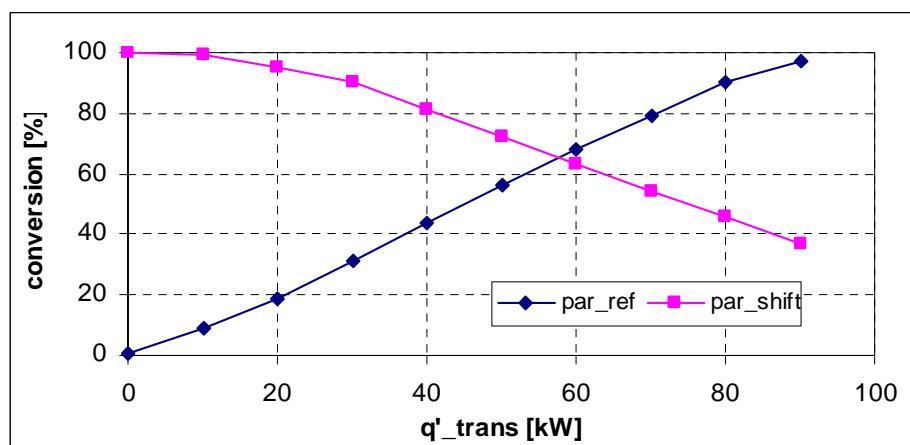
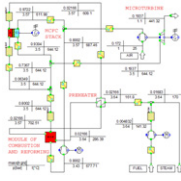


Fig. 6



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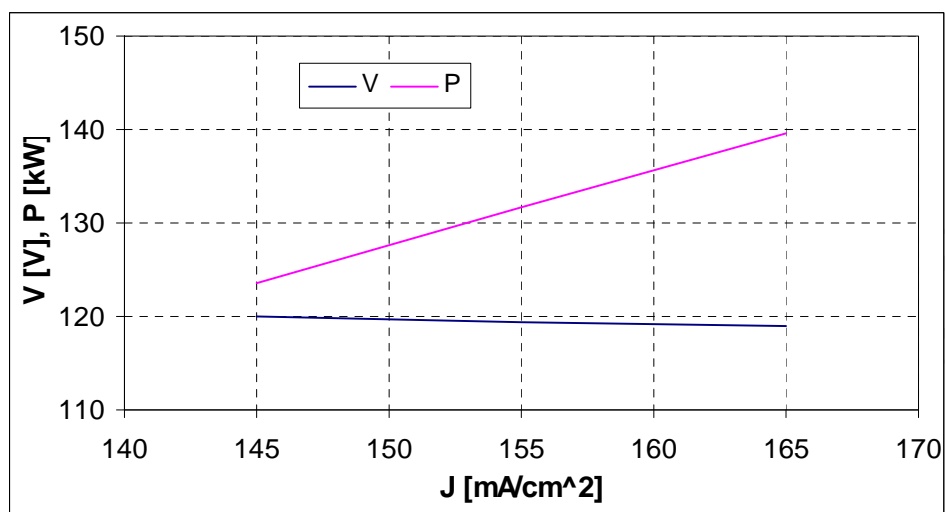


Fig. 8

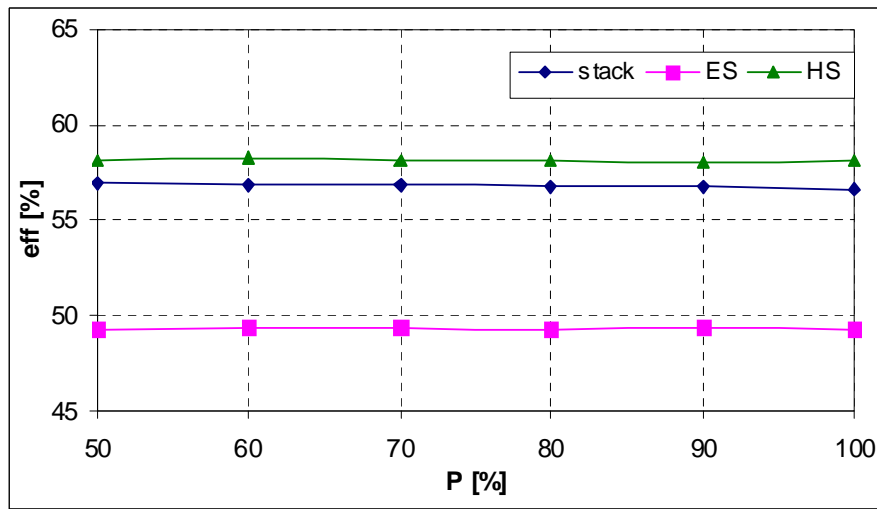


Fig. 9

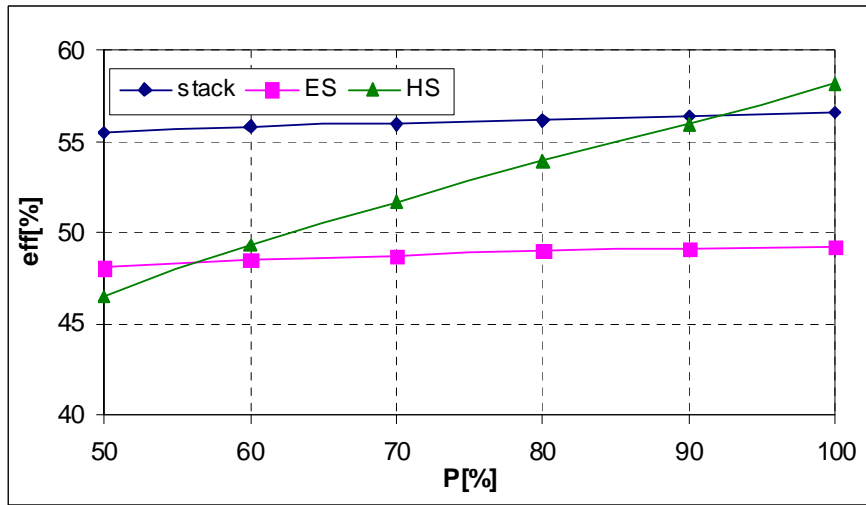


Fig. 10