



Comparison of the behaviour of the CHP-100 SOFC Field Unit fed by natural gas or hydrogen through a computer experimental analysis



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Contents

- > Introduction
 - The EOS Project
- > The CHP SOFC model
 - Model hypothesis for the comparison of NG and H2 feeding...some results
- > Design of the experiments
 - Methodology: 2^k Factorial Analysis
 - Geometric view of the experimental design
- > Analysis of the experiments
 - RSD (Response Surface Design) Methodology
 - Results
- > Conclusions



Introduction: the EOS Project

- > The project foresees four years of activity: 2004-2008
- > As a first phase of the program, the Pennsylvania-based Stationary Fuel Cell division of Siemens Westinghouse Power Corporation supplied GTT with a CHP Solid Oxide Fuel Cell (SOFC) system, fuelled with natural gas with internal reforming, rated **100 kW_e** and **60 kW_{th}**.
- > The unit was previously installed in Westervoort (NL) and in Essen (D), where it operated for more than 20,000 hours.
- > The joint start-up team (SWPC, GTT, Politecnico di Torino) completed the commissioning on June 19, 2005.
- > The system will provide heating and cooling for the facility's buildings upon integration with district HVAC.
- > The system is grid-connected.
- > Operation Data on December 13, 2005 (08.00 pm):



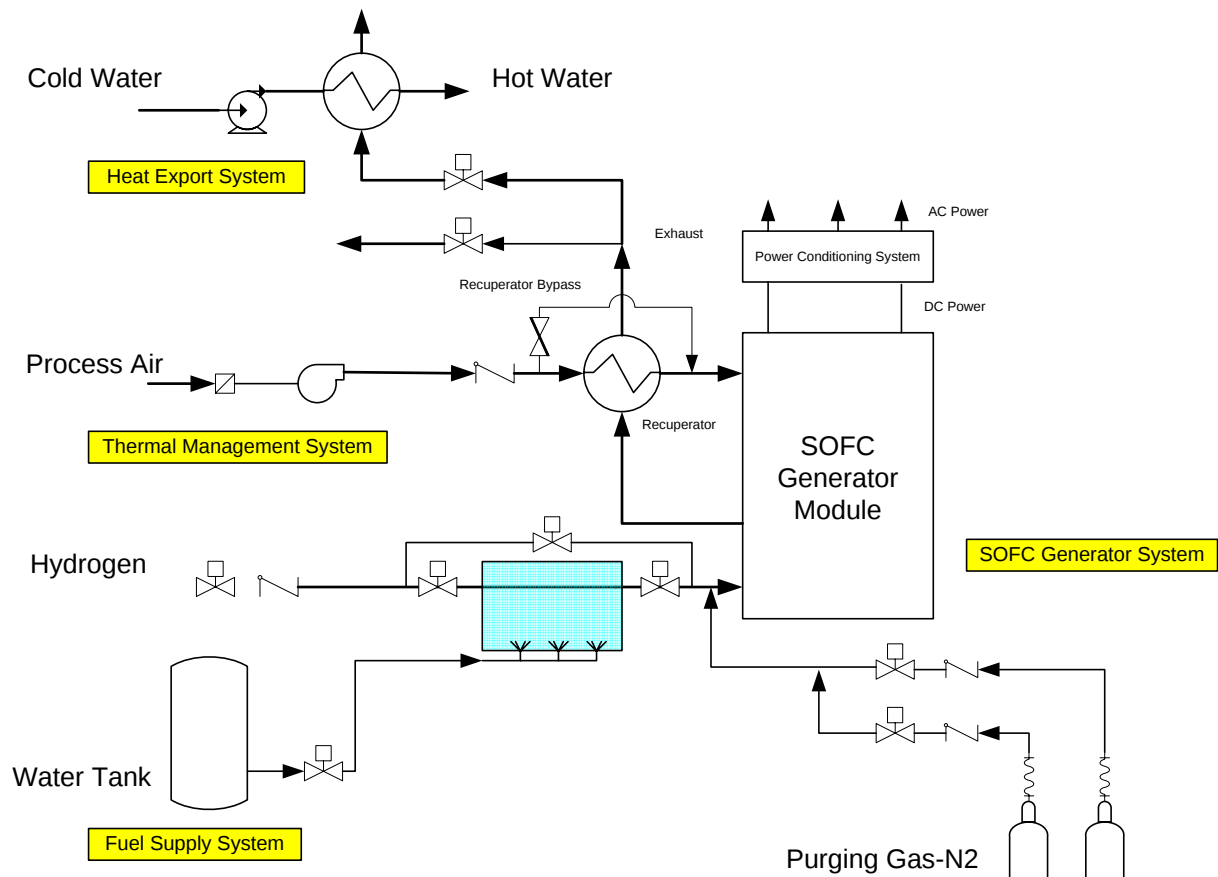
Run hours in GTT	4250 h
Total Run hours	around 25000 h
Energy produced in GTT	507.2 MWh
Produced Power, DC	122.7 kW
Produced Power, AC	102 kW



The CHP SOFC Model

In the future plans, there is a possibility of **local production of hydrogen at low prices (from hydroelectricity)** in the country around Torino. It could become of interest the development of an alternative SOFC BoP structure fed by wet hydrogen in place of natural gas.

The first step is a preliminary comparison of the two options through the use of an analytical model.



The CHP SOFC Model

Electrochemical Model, Chemical Model, Mass and Energy Balance of the Fuel Cell Generator and the whole CHP plant

Electrochemical Model

Activation overpotential $\eta_{act,a/c}$

$$\begin{aligned} \text{Cathode} \quad \frac{1}{R_a} &= K_a \cdot \frac{2 \cdot F}{R \cdot T} \cdot \left(\frac{p_{H_2}}{p^0} \right)^{m_a} \cdot \exp \left(- \frac{E_a}{R \cdot T} \right) \\ \text{Anode} \quad \frac{1}{R_c} &= K_c \cdot \frac{4 \cdot F}{R \cdot T} \cdot \left(\frac{p_{O_2}}{p^0} \right)^{m_c} \cdot \exp \left(- \frac{E_c}{R \cdot T} \right) \end{aligned}$$

Ohmic Overpotential η_{ohm}

$$\eta_{ohm} = i \cdot \sum_j r_j \quad r_j = \rho_j \cdot t_j$$

$$\begin{aligned} \text{Anode} \quad \rho_a &= 0.008114 \cdot \exp \left(\frac{600}{T} \right) \\ \text{Electrolyte} \quad \rho_{el} &= 0.00294 \cdot \exp \left(\frac{10350}{T} \right) \\ \text{Cathode} \quad \rho_c &= 0.00298 \cdot \exp \left(\frac{-1392}{T} \right) \\ \text{Interconnection} \quad \rho_{int} &= 0.1256 \cdot \exp \left(\frac{4690}{T} \right) \end{aligned}$$

Concentration Overpotential $\eta_{conc,a/c}$

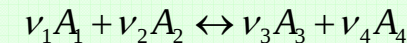
$$\text{Anode/Cathode} \quad \eta_{conc,a/c} = \frac{R \cdot T}{n \cdot F} \cdot \ln \left(1 - \frac{i}{i_{l,a/c}} \right)$$

Constants:

$$\begin{aligned} \text{Activation energy of anode } 110 \text{ kJ/mol} \quad m_a &= 0.25 \\ \text{Activation energy of cathode } 160 \text{ kJ/mol} \quad m_c &= 0.25 \\ \text{Pre-exponential coefficient for anode} \quad K_a &= 2.13 \cdot 10^8 \text{ A/m}^2 \\ \text{Pre-exponential coefficient for cathode} \quad K_c &= 1.49 \cdot 10^{10} \text{ A/m}^2 \\ i_{l,a/c} &= 0.8716 T_{gen}^{-546.8} \text{ mA/cm}^2, \text{ fitted from literature [7]} \end{aligned}$$

Chemical Model

The steam reforming and water shift reactions are considered at the equilibrium



$$K_p = \frac{y_{A_3}^{\nu_3} \cdot y_{A_4}^{\nu_4}}{y_{A_1}^{\nu_1} \cdot y_{A_2}^{\nu_2}} \cdot \left(\frac{p}{p^0} \right)^{-\nu_1 - \nu_2 + \nu_3 + \nu_4}$$

$$K_p = \frac{\left[\frac{k_3 - \zeta \cdot (\nu_3 / \nu_1)}{n_{tot}} \right]_{A_3}^{\nu_3} \cdot \left[\frac{k_4 - \zeta \cdot (\nu_4 / \nu_1)}{n_{tot}} \right]_{A_4}^{\nu_4}}{\left[\frac{k_1 - \zeta}{n_{tot}} \right]_{A_1}^{\nu_1} \cdot \left[\frac{k_2 - \zeta \cdot (\nu_2 / \nu_1)}{n_{tot}} \right]_{A_2}^{\nu_2}} \cdot \left(\frac{p}{p^0} \right)^{-\nu_1 - \nu_2 + \nu_3 + \nu_4}$$

$$\log K_p = A \cdot T^4 + B \cdot T^3 + C \cdot T^2 + D \cdot T + E$$

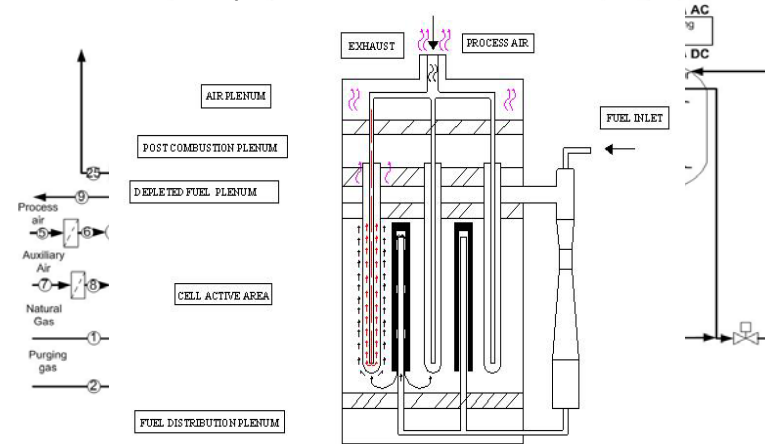
Fuel Cell Generator Energy Balance Model

$$W_{el} = \sum_{in} H_{in} - \sum_{out} H_{out} - \phi_{th} - \phi_{d_1} + \sum_K \dot{N}_k (-\Delta H)$$

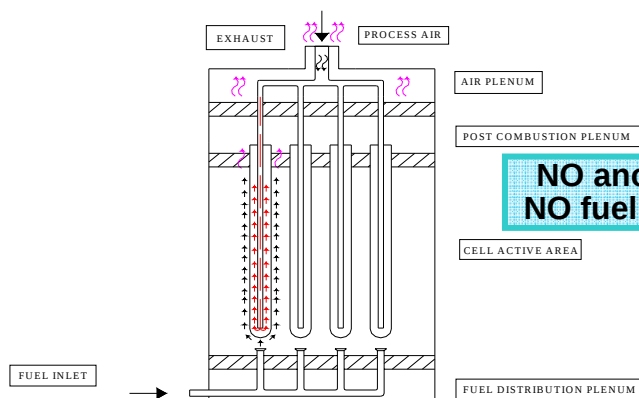


The CHP SOFC Model

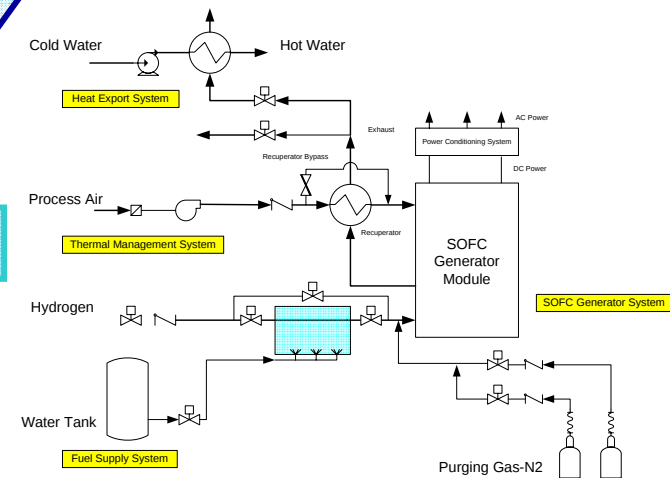
The CHP-100 kWe SOFC Field Unit (SWPC)



CHP SOFC Field Unit fuelled with Hydrogen: simplified flow schematics and generator lay-out



**NO anode recirculation
NO fuel depleted plenum**



The CHP SOFC Model:

Model hypothesis for the comparison of NG and H₂ feeding. Some results

- The fuel utilization is fixed equal in both the plants
- The two SOFC plants operate at the same air stoichs in order to have the same power required for the air blowers
- The performances are evaluated at the same average generator temperature. In order to achieve this, the two systems run with different air temperatures at the inlet canister: the Hy plant works at lower inlet canister air temperature because no endothermic reforming reaction occurs inside the SOFC stack

System operation	Natural Gas	Hydrogen
Fuel Composition	85.5% CH ₄ ; 13.5 N ₂ ; 1% CO ₂	97% H ₂ ; 3% H ₂ O
Fuel flow rate (kg/hr)	22.00	10.85
Air inlet flow rate (kg/h)	1364.4	1364.4
Air stoichiometric ratio	5.55	5.55
Stack temperature (°C)	970	970
Overall fuel utilization (%)	85	85
Recirculation ratio (% of anodic product)	62	0
DC power (kW)	129.14	140.20
Single cell voltage (V)	0.666	0.729
Generator voltage (V)	256	280
Auxiliary power consumption (kW)	9.49	9.49
System exhaust temperature (°C)	226	320

Fixed Air
Stoichs

Fixed Generator
Temperature

Fixed Fuel
Utilization

At nominal operation point (I=500 A)

	NG	HY
Generator Voltage (V)	256	280
System Exhaust Temperature (°C)	226	320



Design of the experiments: 2^k Factorial Analysis

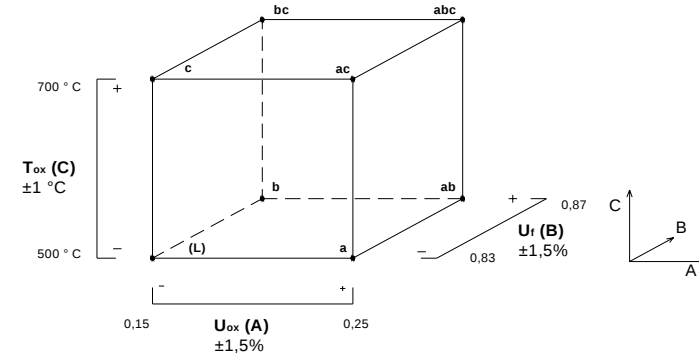
- 2³ Factorial Analysis on a computer model: Yates's Test
Analyzed Factors (*Independent Variables*)
 1. Air Utilization Factor, U_{ox}
 2. Fuel Utilization Factor, U_f
 3. Air Temperature at the inlet canister, T_{ox}
- Completely Randomized Design
Three repetitions for each designed treatment and analysis of variance of the results (ANOVA)
- Factorial Analysis performed at three different generator current levels:
 - 400 Amps (0.16 A/cm²)
 - 500 Amps (0.20 A/cm²)
 - 600 Amps (0.24 A/cm²)



Design of the experiments: Geometric view of the experimental design

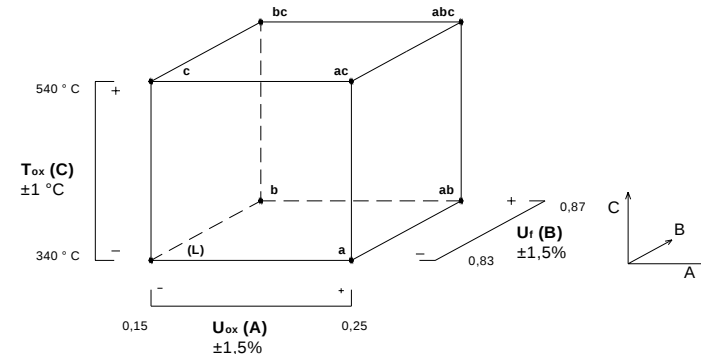
Cube Plot:

Yates's treatment for the NG fuel



Cube Plot:

Yates's treatment for the Hy fuel



Investigated Dependent Variables:

Average Generator Voltage

Generator Exhausts' Temperature

Feature of the Design:

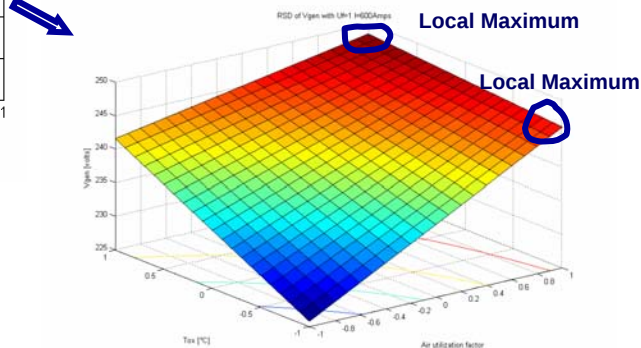
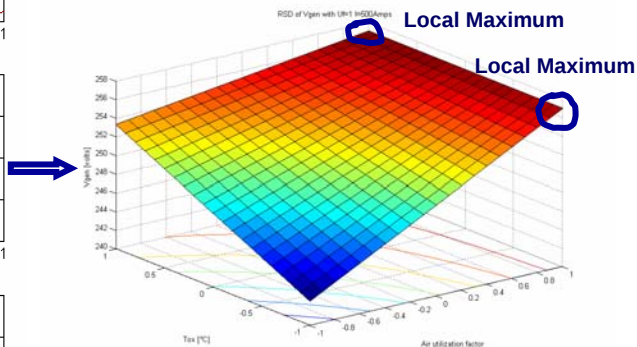
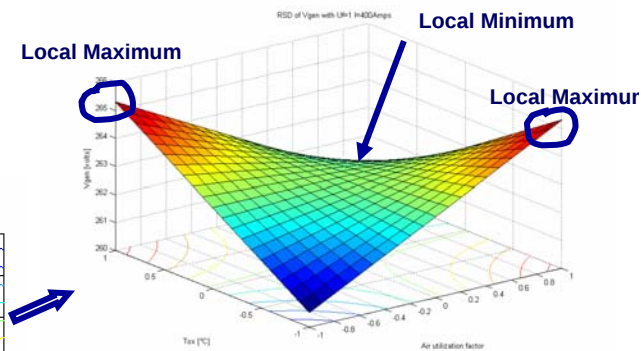
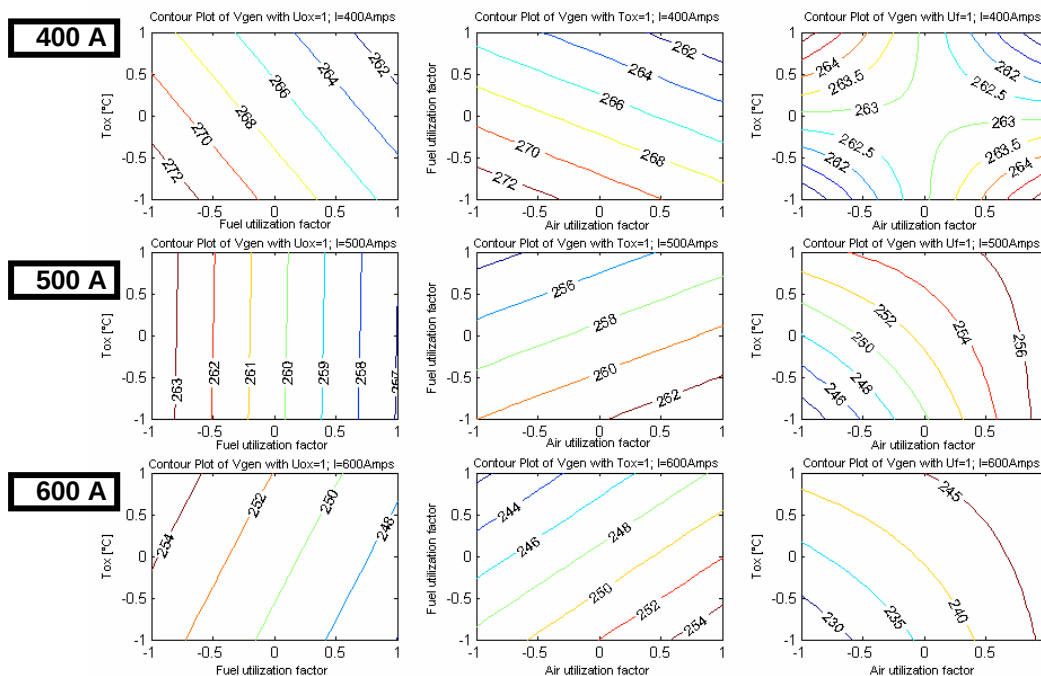
With the simple 2^k factorial analysis it is possible to obtain a First-Order Regression Model for the investigated dependent variables



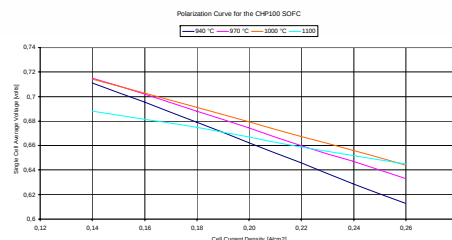
Analysis of the experiments: Results

Effect of the interactions of the factors
for the three current levels:

**NG plant- Generator Voltage
dependent variable**



**Effect of the generator
temperature on the
polarization curve**



Analysis of the experiments: Results

NG SOFC plant: Exhaust's Temperature at 500 Amps

- **U_{ox} factor:** **Positive** effect when it is at its upper level (0.25). The generator is less cooled and the exhausts's temperature rises up (73% of the total variability of the dependent variable).
- **U_f factor:** **Negative** effect when it is at its upper level (0.87). This is due to the fact that less heat is recovered in the combustion zone because a smaller amount of fuel is burned (2% of the total variability of the dependent variable)
- **T_{ox} factor:** **Negative** effect when it is at its upper level (700°C). The pre-heating of the process air in the thermal managment skid has the effect of the reduction of the exhausts' temperature in the heat export system (HES) (24% Of the total variability of the dependent variable)

First-Order Regression model: $T_{exh} = 252.9 + 43.2 \cdot U_{ox} - 7.1 \cdot U_f - 24.6 \cdot T_{ox}$

Hy SOFC plant: Exhaust's Temperature at 500 Amps

- **U_{ox} factor:** **Positive** effect when it is at its upper level (0.85). The generator is less cooled and the exhausts's temperature rise up (85% of the total variability of the dependent variable, higher than in case of NG feeding).
- **U_f factor:** **Negative** effect when it is at its upper level (0.87). This is due to the fact that less heat is recovered in the combustion zone because a smaller amount of fuel is burned (2.4% of the total variability of the dependent variable)
- **T_{ox} factor:** **Negative** effect when it is at its upper level (540°C). The pre-heating of the process air in the thermal managment skid has the effect of the reduction of the exhausts' temperature in the heat export system (HES) (12% of the total variability of the dependent variable, lower than in case of NG feeding)

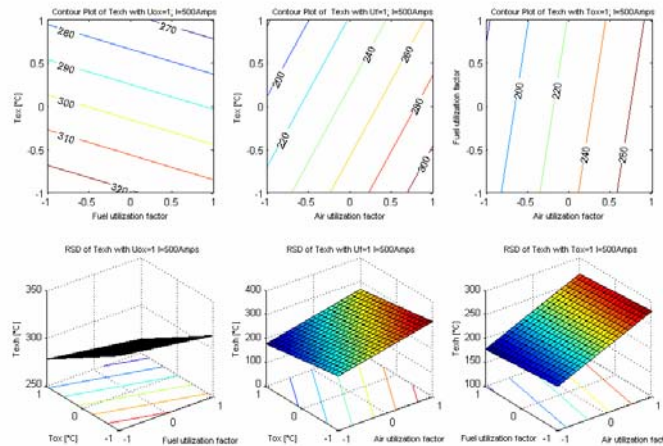
First-Order Regression model: $T_{exh} = 337.9 + 61.9 \cdot U_{ox} - 10.3 \cdot U_f - 23.8 \cdot T_{ox}$



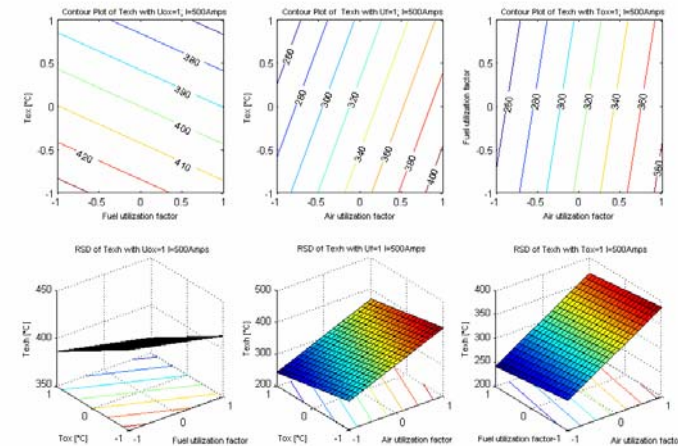
Analysis of the experiments: Results

Response Surface Analysis of the Exhaust's Temperature at 500 Amps

NG SOFC PLANT



Hy SOFC PLANT



The observed behaviour is similar for the other current levels

The air pre-heating T_{ox} has a negative main effect on both plants when the factor is at its high level. In the plant fed with natural gas the reduction of this temperature has more positive effect on the exhausts' temperature than in the plant fed with hydrogen (24% of the total variability for NG and 12% for Hy)

Working at high air utilization factor has a positive effect on the exhaust temperature, but in order to achieve high recovered thermal power the air-preheating should be minimized, and this is obtained imposing a low T_{ox} value (the factor which mainly affects the recovered heat) while the U_{ox} factor has a reduced effect



Conclusions

GENERATOR VOLTAGE

- > The air utilization factor has a positive main effect when it is at its upper level on the voltage for currents over 500 Amps (ohmic overvoltages prevail)
- > The fuel utilization factor has a negative main effect when it is at its upper level on the voltage for the NG plant, while for the Hy plant the effect is negligible (for this plant the H₂ partial pressure at the anode side is already high)

EXHAUSTS TEMPERATURE

- > The air-preheating has a negative effect when it is at its upper level on the exhausts' temperature, while the air utilization factor has a positive main effect.

FINAL CONSIDERATION

- > The H₂ fuel seems to obtain a higher DC generated electric power and above all a higher recovered heat. The cooling of the generator with the H₂ fuel is really a challenge. The upper value of the factor U_{ox} chosen in this work (0.25) is too high with respect to the maximum allowed generator temperature:

Upper Bound of U_{ox} in order to obtain safe generator temperature operating conditions in Hy feeding ($T_{gen} < 1000^{\circ}C$):

$$\text{If } T_{ox} = 540^{\circ}C \text{ then } U_{ox} \leq 0.17$$

$$\text{If } T_{ox} = 340^{\circ}C \text{ then } U_{ox} \leq 0.20$$



Future Work

- > The methodology is now implemented in the benchmark characterization of the CHP100 SOFC Field Unit during the experimental campaign at the Gas Turbine Technologies (GTT) in Torino
- > On field experiments have been designed for fitting desired regression model (First-Order or Higher Order Regression models) by applying factorial analysis: 2^k factorial, 2^k factorial with central composite design (CCD), 3^k factorial
- > The aim are the physical characterization of the generator, the definition of the regression models for some chosen dependent variables (multiple response problem) and the application of constrained optimization methods to find optimum operating conditions for W_{el} and W_{th} at different current levels
- > A lower size plant (5 kW_{el}) will be fed with Hydrogen in order to experimentally analyze its behaviour.
- > A Website provides further information about the EOS project: visit it!

www.eos.polito.it

