



Benchmark characterization of a tubular SOFC CHP generator: model description and experimental validation



M. CALI', F.DE BENEDICTIS*, M. SANTARELLI, P. LEONE, V. VERDA

Dipartimento di Energetica. Politecnico di Torino

Corso Duca degli Abruzzi 24, 10129 Torino (Italy)

*Gas Turbine Technologies, Corso Romania 661 Torino (Italy)

e-mail: pierluigi.leone@polito.it



ASME EFC05

Roma

14-16 December 2005

Contents

- > Introduction
 - The EOS Project
- > Overview of the SOFC CHP100 operation
- > The SOFC CHP100 model
 - Electrochemical model
 - Chemical model
 - Thermal model
- > Model Validation
 - Results
 - Comments
- > 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 next step is the installation and the demonstration of the SFC200 (SWPC) planned for the 2007, rated **125 kW_e** and **85 kW_{th}**.
- > Also a tubular SOFC CHP5 (SWPC and FCT) will be tested since early 2006.



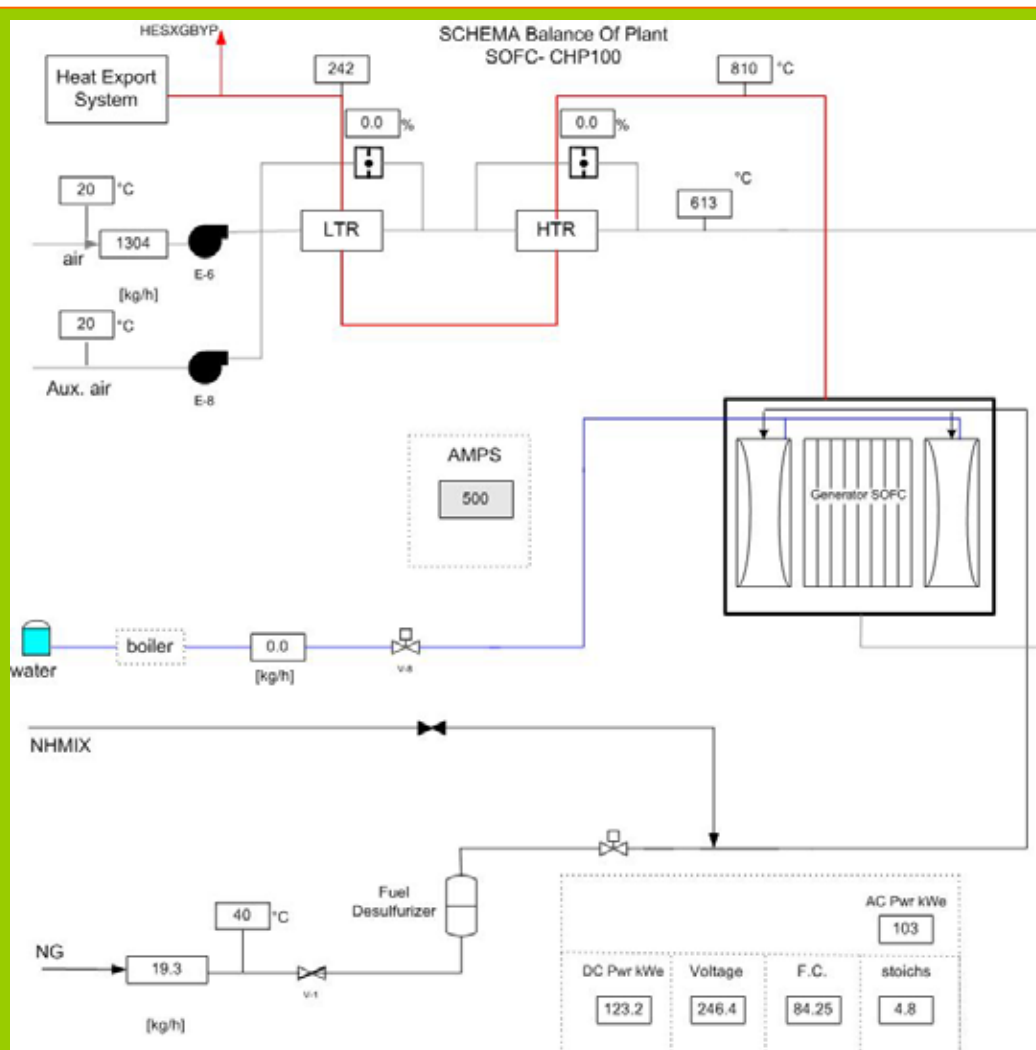
Operation Data of the SOFC CHP100 on December 13, 2005

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



Overview of the SOFC CHP 100 operation

Some Experimental Results (November 2005)



System operation

Generator Current [A]	500
Air inlet flow rate (kg/h)	1304
Stack temperature (°C)	958
Overall fuel utilization (%)	84.25
System exhaust temperature (°C)	242
DC power (kW)	123.2
Auxiliary power consumption (kW)	9.5
AC power (kW)	103
Thermal power (kW)	57
Water Inlet Temperature (°C)	84
Water Outlet Temperature (°C)	96
Run hours in GTT (h)	3950

Operation data of the CHP 100 on November 30, 2005

Thermal Management System



Fuel Supply System



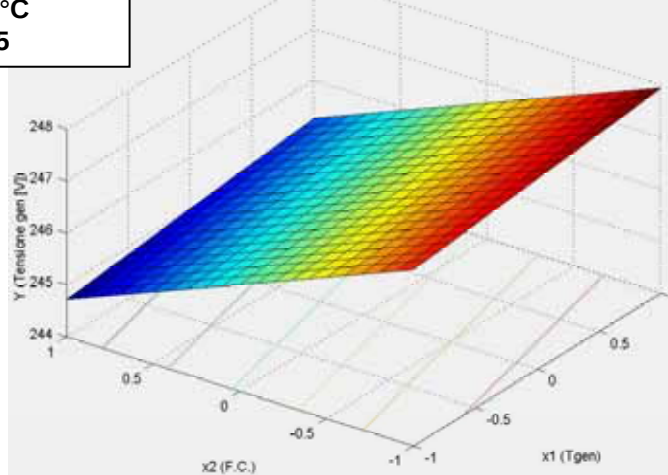
Overview of the SOFC CHP 100 operation

Some Experimental Results (November 2005)

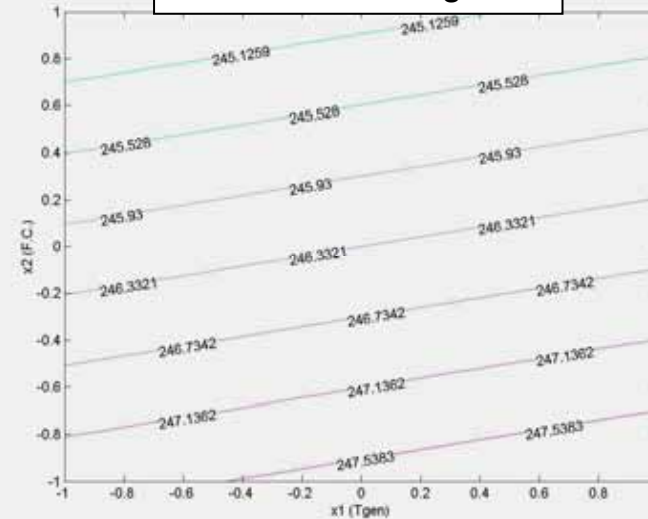
TESTED EXPERIMENTAL
DOMAIN

$951^{\circ}\text{C} < T_{\text{gen}} < 961^{\circ}\text{C}$
 $81.75 < \text{F.C.} < 84.25$

Response Surface V_{gen}



Contour Plot V_{gen}



TESTED EXPERIMENTAL DOMAIN:

$951^{\circ}\text{C} < T_{\text{GEN}} < 961^{\circ}\text{C}$

$81.75 < \text{F.U.} < 84.25$

SET UP TEMPERATURE SENSITIVITY OF THE GENERATOR VOLTAGE

55 mV/°C

FUEL UTILIZATION SENSITIVITY OF THE GENERATOR VOLTAGE

-1 V/%FU



Some Experimental Results (November 2005)

TESTED EXPERIMENTAL DOMAIN: $951^{\circ}\text{C} < T_{\text{GEN}} < 961^{\circ}\text{C}$
 $81.75 < \text{F.U.} < 84.25$

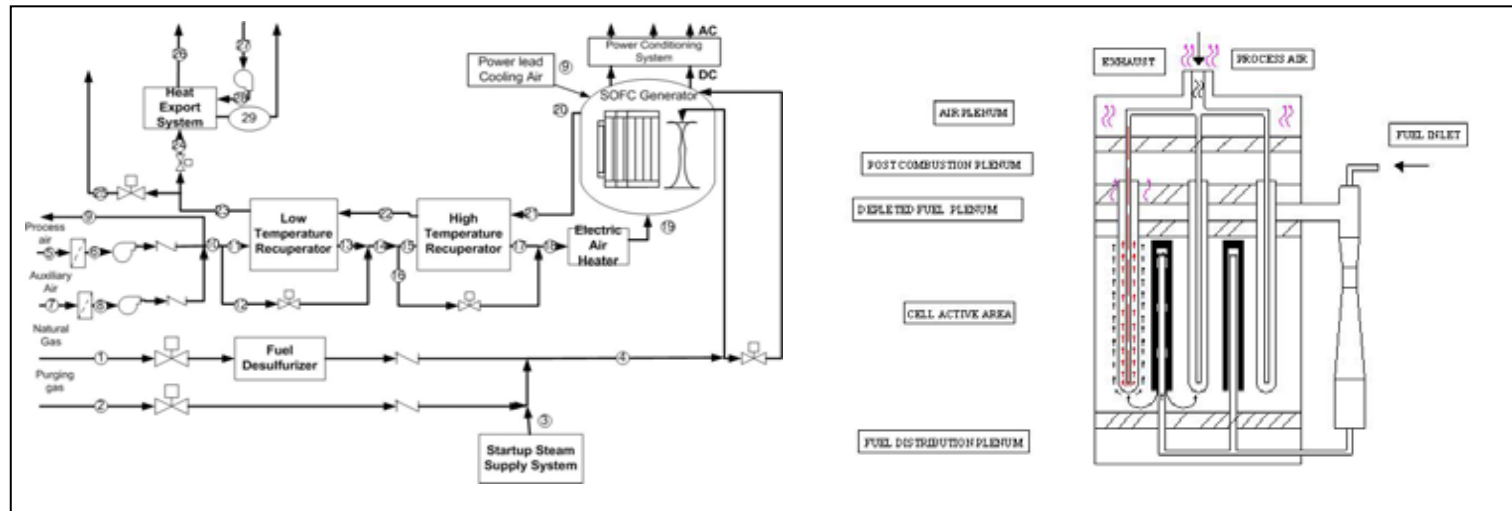
SET UP TEMPERATURE SENSITIVITY OF THE GENERATOR VOLTAGE
 $55 \text{ mV}/^{\circ}\text{C}$

FUEL UTILIZATION SENSITIVITY OF THE GENERATOR VOLTAGE
 $-1 \text{ V}/\%\text{FU}$



The SOFC CHP100 Model

- > A mathematical model has been developed with the aim of simulating the steady state operation of the SOFC CHP100 built by Siemens



- > For a certain current demand the model is able to calculate the required fuel flow, the generator voltage, gas composition in several points, the net AC power and the recovered heat for the cogeneration
- > The average generator temperature is an input parameter and is calculated iteratively by tuning the air preheating (simulating the recuperator by-pass valves) and the air utilization factor (simulating different air blower speeds). For a set current demand the air preheating is fixed at a suitable value and the set-up temperature is regulated by tuning the oxidant utilization



Electrochemical model

Electrochemical Model

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

$$\text{Cathode} \quad \frac{1}{R_a} = K_a \cdot \frac{2 \cdot F}{R \cdot T} \cdot \left(\frac{p_{H_2}}{p^0} \right)^{m_a} \cdot \exp \left(- \frac{E_a}{R \cdot T} \right)$$

$$\text{Anode} \quad \frac{1}{R_c} = K_c \cdot \frac{4 \cdot F}{R \cdot T} \cdot \left(\frac{p_{O_2}}{p^0} \right)^{m_c} \cdot \exp \left(- \frac{E_c}{R \cdot T} \right)$$

Ohmic Overpotential η_{ohm}

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

$$\text{Anode} \quad \rho_a = 0.008114 \cdot \exp \left(\frac{600}{T} \right)$$

$$\text{Electrolyte} \quad \rho_{el} = 0.00294 \cdot \exp \left(\frac{10350}{T} \right)$$

$$\text{Cathode} \quad \rho_c = 0.00298 \cdot \exp \left(\frac{-1392}{T} \right)$$

$$\text{Interconnection} \quad \rho_{int} = 0.1256 \cdot \exp \left(\frac{4690}{T} \right)$$

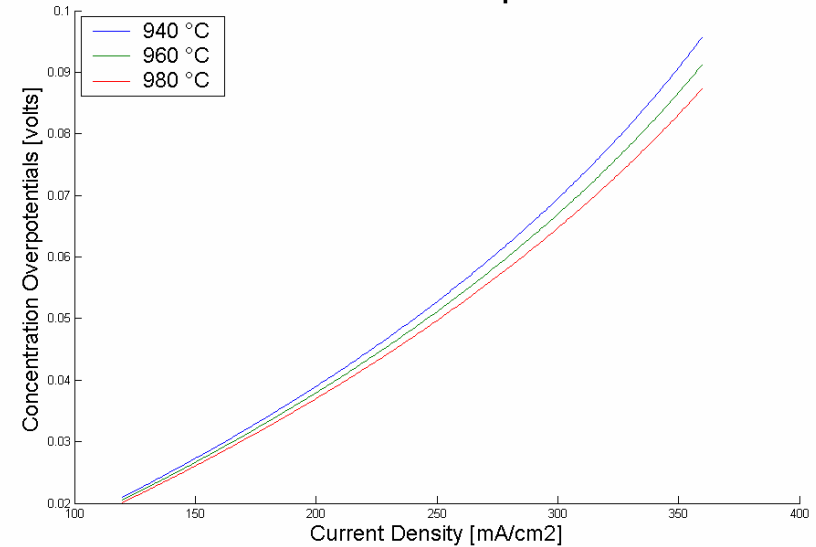
Concentration Overpotential $\eta_{conc, a/c}$

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

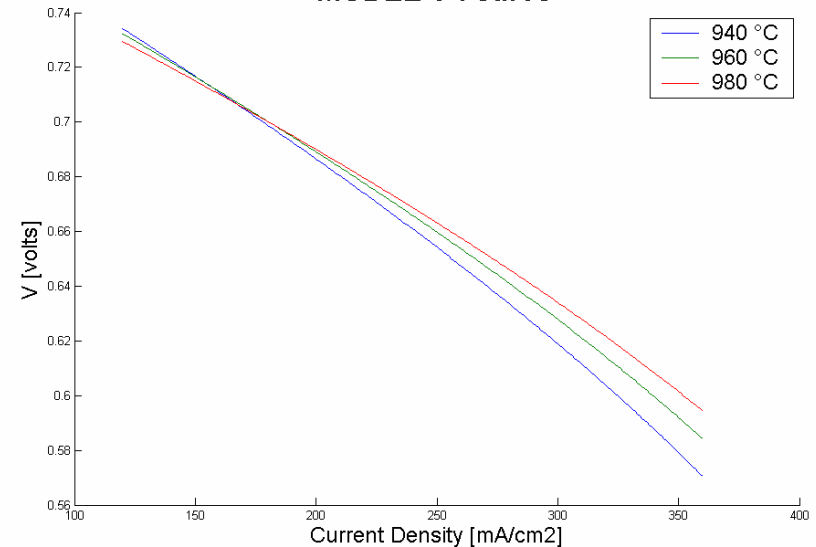
Constants:

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

Concentration Overpotentials



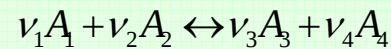
MODEL V-I curve



Chemical Model

Chemical Model

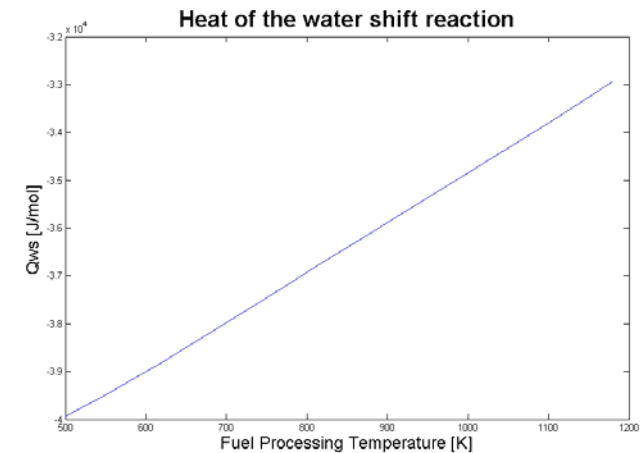
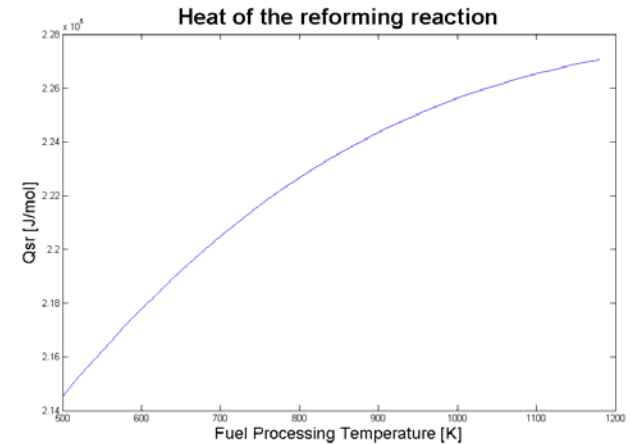
The steam reforming and water shift reactions are considered at the equilibrium



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

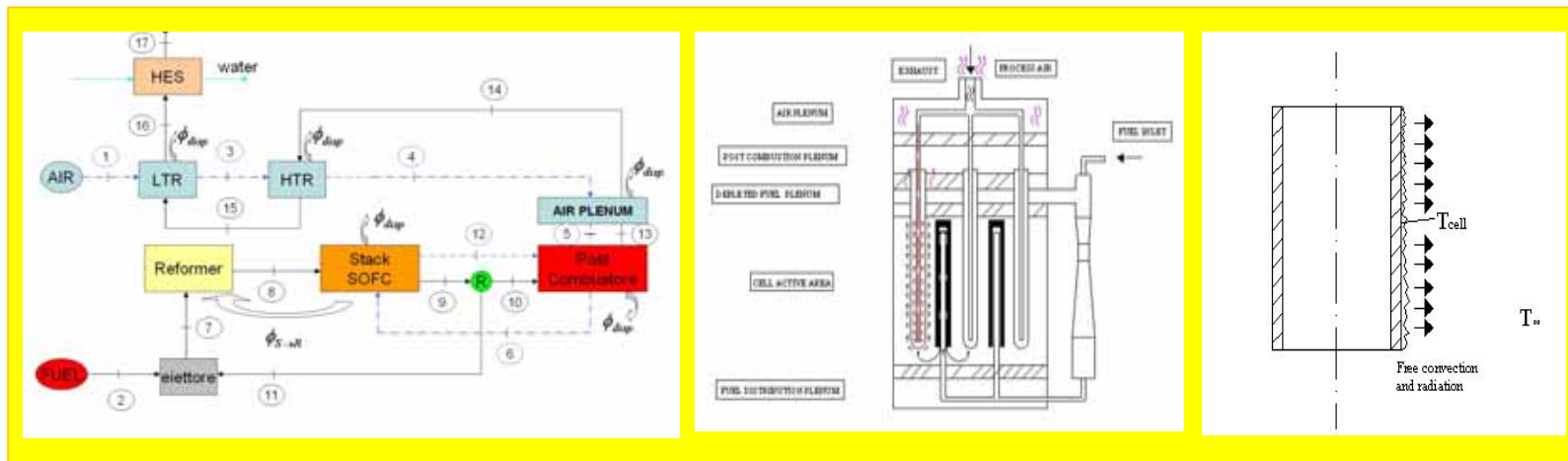
$$K_p = \frac{\left[\frac{k_3 - \zeta \cdot (\nu_3 / \nu_1)}{n_{tot}} \right]_{A_3}^{\nu_3} \cdot \left[\frac{k_4 - \zeta \cdot (\nu_4 / \nu_1)}{n_{tot}} \right]_{A_4}^{\nu_4}}{\left[\frac{k_1 - \zeta}{n_{tot}} \right]_{A_1}^{\nu_1} \cdot \left[\frac{k_2 - \zeta \cdot (\nu_2 / \nu_1)}{n_{tot}} \right]_{A_2}^{\nu_2}}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

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



Thermal Model

- > The equilibrium temperature of the reaction products is evaluated by solving the generator energy balance equation. The heat fluxes associated to the main reactions are taken into account
- > The cell tube temperature has been evaluated by considering a thermal resistance between the cell surface and the gas mixture inside the generator (equivalent electric circuit model)
- > The thermal management system of the SOFC CHP100 is modeled by considering the air preheating of the process air at the LTR and HTR recuperators and in the top section of the generator (Air plenum and combustion zone)



Fuel Cell Generator Energy Balance Model

$$W_{el} = \sum_{in} H_{in} - \sum_{out} H_{out} - \phi_{th} - \phi_{d-1} + \sum_K \dot{N}_k (-\Delta H)$$

$$\bar{T}_{cell} = T_{\infty} + R_t \cdot (\phi_{ech} - \phi_{sr} - \phi_{ws})$$

$$G_{14} h_{14} = \phi_{comb} - \beta_3 \cdot \phi_{pre-heating} + G_{12} h_{12} + G_{10} h_{10}$$

$$G_{13} h_{13} = \phi_{comb} - \beta_2 \cdot \phi_{pre-heating} + G_{12} h_{12} + G_{10} h_{10}$$



Model Validation

- > Some parameters have been estimated in the model validation mainly to better assess the balance of plant model.
- > The parameter estimation has been made on four measured variables using least squares method

Average Operating Temperature
Generator Voltage

Combustion Zone Temperature
Generator outlet temperature

- > The equations used for the regression procedure have been (b labels the estimated parameters)

Estimated Parameters

β_1 Thermal resistance [K / W]

β_2 Fraction of air pre heating in CZ

β_3 Heat Losses in the top section of the generator

β_4 Supplementary overvoltage [volts]

$$T_{cell} = T_g + \beta_1 \cdot (\phi_{ech} - \phi_{ref} - \phi_{shift})$$

$$G_{13} h_{13} = \phi_{comb} - \beta_2 \cdot \phi_{pre-heating} + G_{12} h_{12} + G_{10} h_{10}$$

$$G_{14} h_{14} = \phi_{comb} - \beta_3 \cdot \phi_{pre-heating} + G_{12} h_{12} + G_{10} h_{10}$$

$$V_c = E_{rev} - \eta_{act,a/c} - \eta_{ohm} - \eta_{conc,a/c} - \eta_{reg}$$



Model validation

- > The parameter estimation has been made on two operating points based on field measurements at two different generator currents



System operation		
Condition	start-up	start-up
Fuel Composition	Natural Gas	Natural Gas
Generator current (A)	450	470
Fuel flow rate (kg/hr)	17.98	18.1
Air inlet flow rate (kg/h)	1287	1313
Air stoichiometric ratio	5.5	5.4
Stack temperature (°C)	940	960
Overall fuel utilization (%)	82.75	82.75
Single cell voltage (V)	0.633	0.631
Generator voltage (V)	243.1	242.3
System exhaust temperature (°C)	240	245
DC power (kW)	100	114
AC power (kW)	90	94

- > The main results of the estimation suggest that in the combustion zone occurs the 30% of the air preheating at the top section of the generator.
- > The estimated supplementary cell overpotential is around 50 mV/cell

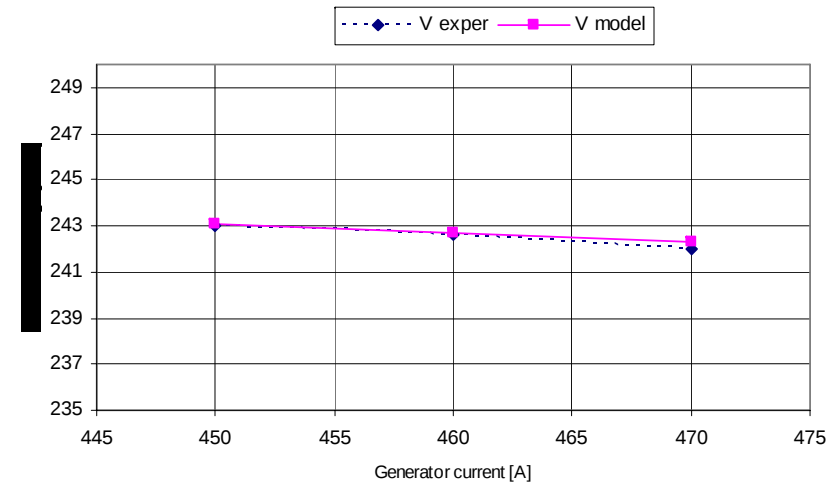
Estimated Parameters	450 A	470 A
β_1 [kW]	$9.2 \cdot 10^{-4}$	$1.27 \cdot 10^{-3}$
β_2	0.25	0.31
β_3	$6.9 \cdot 10^{-2}$	$6 \cdot 10^{-2}$
β_4 [mV]	57	52



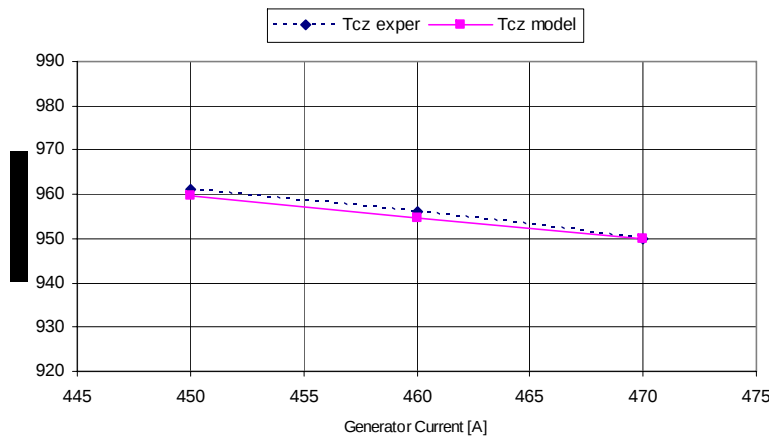
Model validation: Results

The validation of the model has been performed in a small experimental domain because the major efforts have been devoted to the assesment of the operation of the SOFC CHP100. The model error on the estimation variables is above 1% while the validation on the other measured variables has an estimated error value lower than 3%

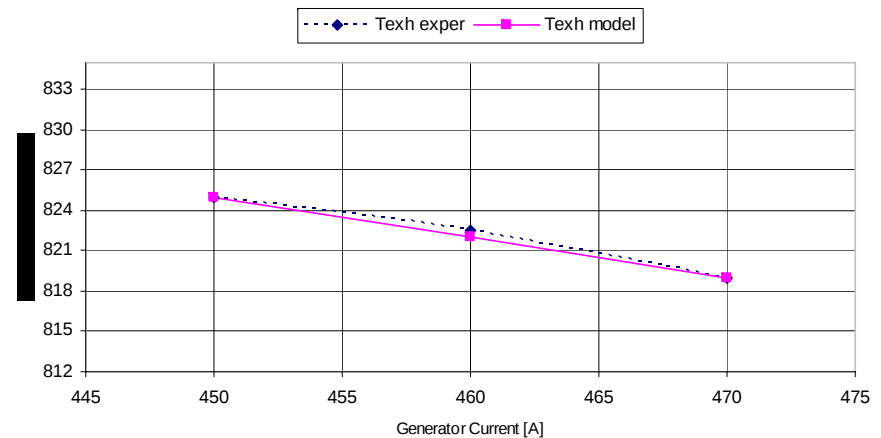
Average Generator Voltage



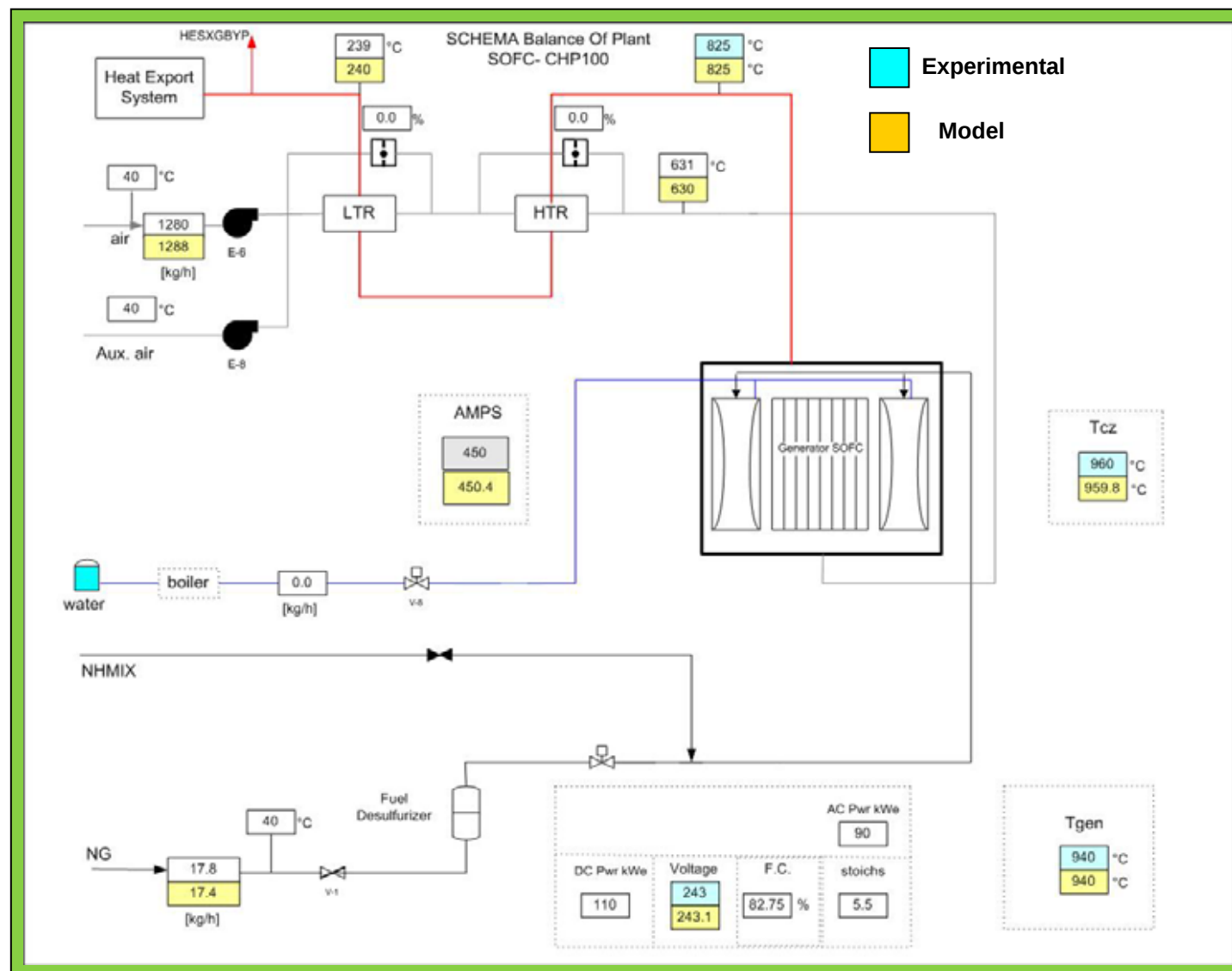
Combustion Zone Temperature



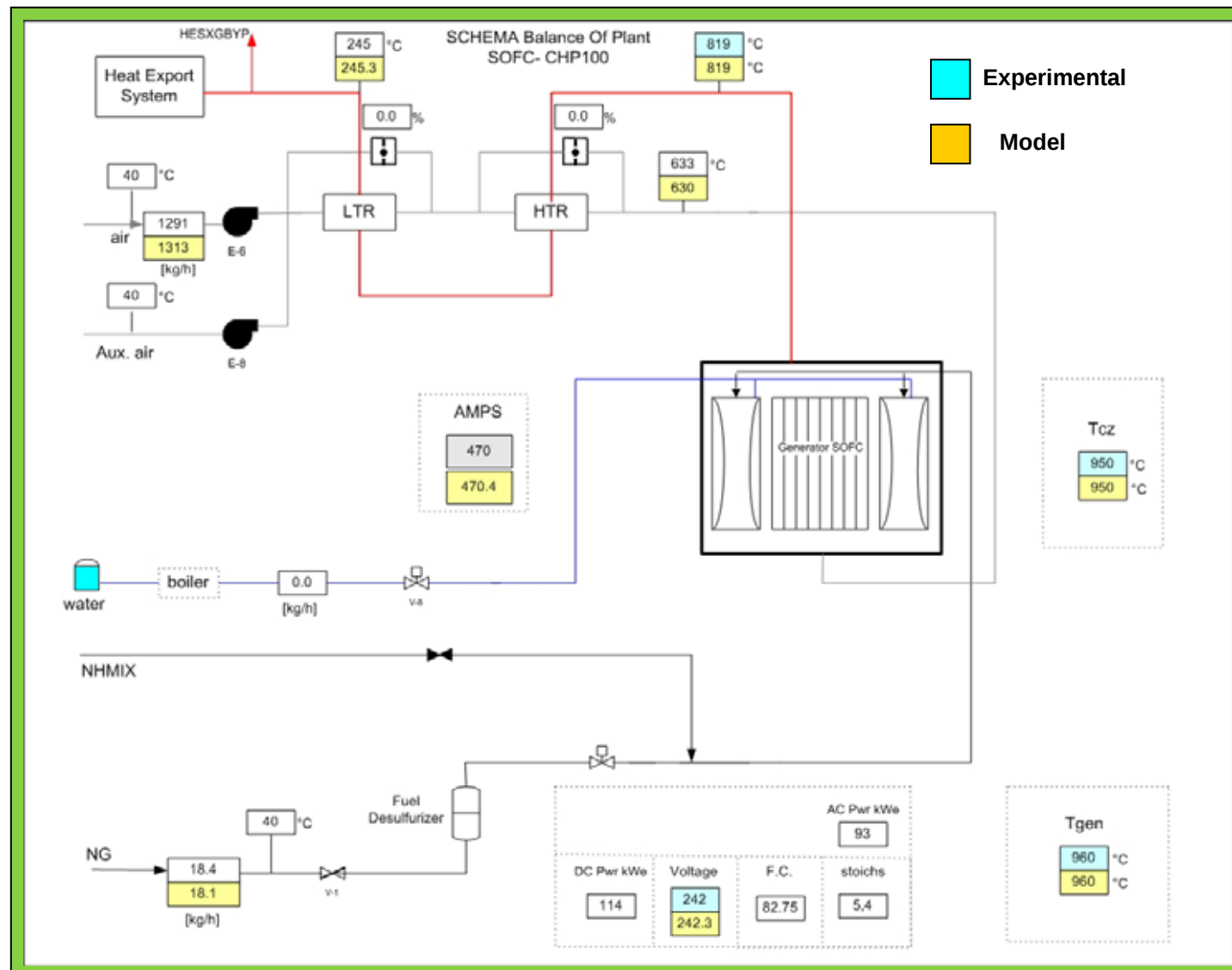
Generator Outlet Temperature



Model validation: Results



Model validation: Results



Model validation: Comments

- > A consideration should be made about the estimated cell overvoltage. A value of **around 50 mV/cell** has been found: this is an overvoltage which is **NOT modeled** by the electrochemical equations used in the polarization model; at the same time this is quite an high value. Our **hypothesis** is that many factors contribute to this behavior, such as:

-Start-Up Conditions

- Not complete conditioning of some SOFC segments
- Not optimal assessment of the Fuel Desulfurizer System with an increasing of the activation overpotential
- Different electrochemical behavior of the SOFC cell bundles because of different pedegrees

Estimated time for the **fuel cell conditioning**: more than 3000 hours

The validation data are obtained for the operation with **zeolites** as desulfurizer agent; the small effectiveness or a NOT good placement of the agent could NOT ensure a good fuel desulfurization affecting the activation losses. Swichting to **activated carbons** led to higher segment voltages.

The pedegrees mainly concern different **total running hours of the cell bundles** but also different providers of the cell materials



Conclusion

- > A mathematical model has been developed simulating a SOFC CHP plant and experimentally validated on the operation of the tubular SOFC CHP100 built by Siemens
- > In the investigated experimental domain the model represents the operation of the SOFC CHP100 with a good approximation
- > Results show that the 30% of the air pre-heating in the top section of the generator occurs in the combustion zone
- > The polarization equations assumed by the current literature do not fit the actual electric behavior of the generator mainly because of the different characteristics of the assembled solid oxide tubes. A supplementary overvoltage of around 50 mV/cell has been estimated for fitting the experimental data
- > A first experimental characterization was performed on the generator (**TEST on the T_{Gen} and F.C.)** by applying a spherical central composite experimental design (CCD). A complete test report will be published as soon as possible



Future Work

- > A deeper validation work will be performed taking into account a complete polarization behavior and a validation of the gas composition at the sample points of SOFC CHP100
- > The model will be modified to represent the operation of a smaller size SOFC CHP plant (SOFC CHP5) fuelled with natural gas.
- > The model could be validated through field measurements on a SOFC CHP5 (Siemens-FCT) which will be installed at the Gas Turbine Technologies very soon.
- > The next experimental campaign will concern the evaluation of changes in the S/C ratio on the generator operation

THANKS TO Gas Turbine Technologies (GTT) FOR THE COURTESY

