

International Journal of Engineering & Technology Sciences

Volume 03, Issue 06, Pages 393-407, 2015



Modeling and Performance Evaluation of Standalone Solid Oxide Fuel Cell for aircraft APU- I: model-based steady-state performance (Reforming efficacy)

Golnaz Pourabedin^a, Fatholah Ommi^{b,*}, Pejman Kazempour^c

^{a,b} Department of Mechanical Engineering, Aerospace Faculty, Tarbiat Modares University, Tehran, Iran. ^c Lead Energy Systems and Process Engineer at GE Global Research-Oil & Gas Technology Center, GE Global Research, United States.

* Corresponding author. Tel: +982182883948

E-mail address: fommi@modares.ac.ir

Abstract

Keywords:	Mathematical modeling is an essential tool for the design of solid oxide fuel cells (SOFCs).
Solid Oxide Fuel cell, APU, Aircraft, Reformer , Simulink, Nasa CEA. Modeling.	external reforming planar solid oxide fuel cell stack model for aircraft APU application. The steady-state performance of the cell and the impact of changes in reforming temperature, Steam to Carbon Ratio (STCR) and the amount of excess air are studied. The developed model consists of mass and energy balances, and an electrochemical model. The focus of this study is on application to "more-electric" airplanes with the regional jet used as a case study. A detailed solid-oxide fuel cell model is used to study the effect of various operating parameters on cell performance. Results indicate that by increasing the product power, the number of cells be decreased and consequently, fuel cell system weight at the requested power is reduced. Therefore by selecting optimal conditions in each case, the fuel cell system weight decreased about 6.6 kg (1.5 percent).

Accepted:20 December2015 © Academic Research Online Publisher. All rights reserved.

1. Introduction

Interest in fuel cells as an advanced auxiliary power unit (APU) technology alternative for aircraft has been receiving increased attention in the past years and is being driven by several factors, including emissions, costs, and evolving application requirements. Conventional gas turbine APUs account for 20% of airport ground-based emissions [1].A Solid Oxide Fuel Cell (SOFC) is an electrochemical device which enables a conversion of chemical energy to electric energy with high efficiency and low environmental impact. Typically, SOFC is operated at high temperature under atmospheric or elevated pressures. [2]. Given cell geometry, the performance of an SOFC strongly depends on the operating conditions and the inlet fuel composition. Since SOFCs offer a wide range of operating possibilities, identifying the effect of operating conditions such as air flow rate and inlet fuel composition on the efficiency and power are critical for the optimal operation of SOFCs. Unlike more than models in aircraft APU application, the study presented here is based on a very detailed planar SOFC mathematical model with external jet reforming for aircraft APU application. Thus, the aim of the present work is to perform the simulation of the standalone SOFC system for aircraft APU application. A first step to perform this simulation was to develop the model of the jet fuel reformer needed to transform the jet fuel into H2 and H2O.

2. Mathematical models

2.1. SOFC model

2.1.1. Model description and assumptions

Figure 1 shows an example of an SOFC cell. An SOFC consists of a solid electrolyte layer which can conduct oxygen ions at sufficiently high temperatures, an anode electrode, where fuel oxidation takes place, a cathode electrode where the oxidant reduction occurs, and two channels, one for the fuel, and one for the oxidant. Electrons which are formed at the cathode as a result of the electrochemical reactions provide the current to connected electrical loads [3]. In this study external reformer first convert a primary fuel (jet fuel) into a gas containing a sufficiently high percentage of hydrogen, suitable for the electrochemical oxidation at the anode.



Fig.1: A schematic representation of an SOFC

The SOFC model is derived by writing the appropriate electrochemical and transfer phenomena equations including mass balance (for air and fuel channels), Material Conservation (to calculate the partial pressures) and energy balance (for solid and gas phases) that will be presented in next sections.

According to the nature of non-linear equations, simplification is necessary. Summary of assumptions to simplify these equations are:

1-One-dimensional path for air and fuel channels

2-uniform distribution of inlet gas

3- O²⁻ conducting electrolytes

4- Adiabatic system

5-Only H_2 and O_2 participate in SOFC electrochemical reactions.

6-It is assumed that fuel reformer emissions are filtered out before entering the fuel cell. Therefore, just hydrogen and water vapor enter the fuel cell stack. 7- It is assumed that a heat exchanger transforms reformer output temperature to fuel cell operating temperature.

2.1.2. The electrochemistry model

The corresponding Nernst equation used to calculate the reversible potential is:

$$E_{cell} = E_{0,cell} + \frac{RT}{4F} ln \left[\frac{(p_{H_2}^{ch})^2 p_{O_2}^{ch}}{(p_{H_2O}^{ch})^2} \right]$$
(1)

 $E_{0,cell}$ is a function of temperature and can be expressed as Ref [4].

When the fuel cell is under load, its output voltage is less than open circuit voltage due to activation, ohmic and concentration losses.

$$V_{cell} = E_{cell} - V_{activation,cell} - V_{ohmic,cell} -$$
(2)
$$V_{concentration,cell}$$

Butler-Volmer equation is normally used to calculate the activation voltage drop under high activation condition, the Tafel equation can be used as:

$$V_{\text{activation}} = \frac{RT}{\alpha\beta F} \ln(\frac{i}{i_0})$$
(3)

In this model, only ohmic losses of electrolyte and interconnection are included while the resistance of electrodes is neglected.

$$V_{Ohmic,cell} = V_{ohmic,electrolyte} + V_{ohmic,interconnection}$$
(4)

To obtain concentration losses, in this paper, diffusion surface between flow channels to reaction sites is considered. Therefore, during the reaction process, concentration gradients can be formed due to mass diffusion on catalyst surfaces. The concentration overpotential in the fuel cell can be obtained as:

$$V_{\text{concentration,cell}} = \frac{{}_{\text{RT}}}{{}_{4F}} \left\{ \ln \left[\frac{\left(p_{\text{H}_2}^{\text{ch}} \right)^2 p_{\text{O}_2}^{\text{ch}}}{\left(p_{\text{H}_2}^{\text{ch}} \right)^2} \right] - \ln \left[\frac{\left(p_{\text{H}_2}^{\text{ch}} \right)^2 p_{\text{O}_2}^{\text{ch}}}{\left(p_{\text{H}_2}^{\text{ch}} \right)^2} \right] \right\}$$
(5)

Assume that the effective partial pressures of hydrogen and oxygen at the reaction site are less than those in the electrode channels, while the effective partial pressure of water at the reaction site is higher than that in the anode channel. it is also assumed that only hydrogen in the electrochemical reaction involved. Thus writing the Stefan-Maxwell diffusion equation and solve equations at the reaction site, each component of the gas pressure at the reaction site is calculated:

$$p_{H2}^{*} = p_{H2}^{ch} - \frac{RT_{PEN}l_a}{2FD_{H2,H2O}}i_{den}$$
(6)

$$p_{H20}^{*} = p_{H20}^{ch} + \frac{RT_{PEN}l_{a}}{2FD_{H2,H20}}i_{den}$$
(7)

$$p_{02}^{*} = P_{c}^{ch} - (P_{c}^{ch} - p_{02}^{ch}) \exp(\frac{RT_{PEN}l_{c}}{4FP_{c}^{ch}D_{02,N2}}i_{den})$$
(8)

2.1.3. Mass balance

At this sub- model the pressure and compositions in the fuel and air channels due to the electrochemical reactions is calculated. It is assumed that after external reforming of jet fuel, only the hydrogen and water enter the fuel channel. Thus, the fuel and air channel input respectively consisting of H2, H2O, and O2, N2. The mass balance equations for both air and fuel channels can be written as:

$$\dot{c}_{i,a} \doteq (n_{in,i} - \dot{n}_{out,i})\frac{1}{v_a} +$$
(9)

$$\sum_{j=0x} v_{i,j} r_j \frac{1}{d_a} \qquad i \in \{ H_2, H_2 0 \}$$

$$\dot{c}_{i,c} \doteq (n_{in,i} - \dot{n}_{out,i}) \frac{1}{V_c} + v_{i,Red} r_{Red} \frac{1}{d_c} \qquad (10)$$

$$i \in \{ N_2, Q_2 \}$$

Assuming uniform variation of gas partial pressures during channels and ideal gas equations, the pressure in gas flow channels and mass flow rate for H2, H2O, and O2 at the outlet of the flow channels can be determined.

Local rate of reactants and products to the electric current can be calculated by Faraday's law:

$$r_{Ox} = r_{Red} = \frac{i}{2F}$$
(11)

2.1.4. Energy balance

In the SOFC energy analysis, the different temperature layers can be used to calculate the temperature profiles in the SOFC. To improve the accuracy of the present model, five temperature

layers have been considered, namely PEN, air channel, fuel channel, air interconnector and fuel interconnector. The heat transfer between cells is neglected in this study. Heat conduction through solids of the fuel cell along the thin layers is normally rather weak, as ceramic materials have a low conductivity [5]. Therefore, the thermal conductivity is neglected. Convection and radiation are much stronger [6]. Therefore, heat transport inside the fuel cell occurs mainly by means of radiation, convection, and mass flow.



Fig. 2: Heat transfer inside a planar SOFC

a. PEN energy balance

$\dot{q}_{gen} = \dot{q}_{chem} - \dot{q}_{elec}$	(12)
$\dot{q}_{in,PEN} = \dot{q}_{gen}$	(13)

$\dot{q}_{out,PEN} = \dot{q}_{conv,air} + \dot{q}_{conv,fuel} + \dot{q}_{air,flow} +$	(14)
$\dot{q}_{fuel,flow} + \dot{q}_{Rad,IA} + \dot{q}_{Rad,IF}$	
$\dot{q}_{in,PEN} - \dot{q}_{out,PEN} = m_{PEN}C_{PEN}\frac{dT_{PEN}}{dt}$	(15)

b. Fuel and air channel energy

$\dot{q}_{in,fuel} = \dot{q}_{conv,fuel} + \dot{q}_{fuel,flow}$	(16)
$\dot{q}_{out,fuel} = \dot{q}_{fuel,flow}$	(17)
$\dot{q}_{in,fuel} - \dot{q}_{out,fuel} = m_{fuel} C_{fuel} \frac{dT_F}{dt}$	(18)
$\dot{q}_{in,air} = \dot{q}_{conv,air} + \dot{q}_{air,flow}$	(19)

 $\dot{q}_{out,air} = \dot{q}_{air,flow}$ (20)

$$\dot{q}_{in,air} - \dot{q}_{out,air} = m_{air} C_{air} \frac{dT_A}{dt} \eqno(21)$$

c. Interconnectors energy balance

$\dot{q}_{in,IF} = \dot{q}_{Rad,IF}$	(22)
$\dot{q}_{out,IF} = \dot{q}_{fuel,flow}$	(23)
$\dot{q}_{in,IF} - \dot{q}_{out,IF} = m_{IF}C_{IF}\frac{dT_{IF}}{dt}$	(24)
$\dot{q}_{in,IA} = \dot{q}_{Rad,IA}$	(25)

 $\dot{q}_{out,IA} = \dot{q}_{air,flow}$ (26)

 $\dot{q}_{in,IA} - \dot{q}_{out,IA} = m_{IA}C_{IA}\frac{dT_{IA}}{dt} \tag{27}$

2.1.5. Model geometry

Table 1 shows parameters of ER-SOFC system.

Table 1: Parameters	value of	ER-SOFC	system
---------------------	----------	---------	--------

Parameters	Value	unit
Anode thickness	510×10^{-6}	m
Cathode thickness	34×10^{-6}	m
Electrolyte thickness	10×10^{-6}	m
Interconnector thickness	500×10^{-6}	m
effective Nusselt number in the air channel	5	-
effective Nusselt number in fuel channel	3.6	-
Interconnectors Emissivity Coefficient	0.9	-

2.2. Reformer Model

In aeronautic applications, since Water Steam Reforming (WSR) is unviable because it requires a considerable amount of water and heat for the endothermic reactions, the development of a compact jet fuel reformer has focused on the Auto-Thermal Reforming (ATR) technology.

In the present simulation, the fuel is Jet A and is already purified of species (e.g. sulfur) that may damage the catalyst and therefore contained only hydrogen and carbon.

We assumed that the temperature and pressure are constant at the output of the fuel processor (in order to use the equilibrium method) which is a rather rough approximation. In an overall sense, ATR can be represented as in the reaction is shown in Equation 28.

$$C_{n}H_{m} + n\frac{R}{2}O_{2} + nSH_{2}O \rightarrow nCO_{2}$$

$$+ \left(\frac{m}{2} + 2n\left(1 - \frac{R}{2}\right)\right)H_{2} + \left(S - 2\left(1 - \frac{R}{2}\right)\right)nH_{2}O$$
(28)

In Equation 28, S is the steam to carbon ratio (STCR) and R is the oxygen to carbon ratio (OTCR). It is important to note that Equation 28 is actually the summation of the steam reformation and partial oxidation reactions, with consideration for the water-gas shift that inevitably occurs along with reformation at typical operating temperatures [7].

The following table shows the jet fuel reformer simulation parameters:

Parameter	Unit	Value
n	-	12
m	-	23
Pressure	Atm	1
Temperature	K	a) 723 to 1473
		b) 1223
STCR	-	a) 1.5
		b) 1.5 to 4.5
OTCR	-	0.7

Table2: Jet fuel reformer simulation parameters

To prevent the formation of soot and reducing the amount of hydrogen, OTCR is considered between 0.5 and 1[8]. The NASA Computer program CEA (Chemical Equilibrium with Applications) calculates chemical equilibrium compositions and properties of complex mixtures. CEA represents the latest in a number of computer programs that have been developed at the NASA Lewis (now Glenn) Research Center during the last 45 year. The program is written in ANSI standard FORTRAN by Bonnie J. McBride and Sanford Gordon [9].

The model assumes chemical equilibrium by minimization of Gibbs free energy for the desired temperature and pressure of the reformer (). By varying the reformer temperature and the steam to carbon ratio for different feedstocks the gas composition at equilibrium for each variation can be obtained. The following figures show some results of the simulation.

3. Results and discussion

3.1. Reformer

a. Effect of operating temperature:

The effect of operating temperature was considered in the reformer.

In Figure 3 it can be clearly seen that with increasing temperature higher methane conversion can be reached and the amount of methane conversion above 1000 k is 100%. This figure shows the mole present of other reforming products

versus temperature changes too. In ROT <1050K, by increasing ROT (Reforming Operating Temperature), hydrogen production increases and water vapor production decreases but In ROT>1050K the opposite changes happen. Therefore, the maximum hydrogen production happens at 1050 K.

Compare the results in Figure 3 with experimental data in re [10], shows a similar trend which indicates the model validation.



Fig. 3: Reformer Gas Composition at different temperature

Golnaz Pourabedin et al./ International Journal of Engineering and Technology Sciences (IJETS) 3 (6): 393-407, 2015.



Fig. 4: Reformer Gas Composition from NASA-Glenn Research Center [10].

b. Effect of inlet steam to carbon (S/C) molar ratio:

The two most important parameters of the fuel processor are the steam-to-carbon (STCR) and the oxygen-to carbon (OTCR) ratio. To understand the influence of these two parameters we have done simulations of the reformer for four different steam-to-carbon ratios: 1.5, 2.5, 3.5 and 4.5, for an oxygen-to-carbon ratio of 0.7 (to prevent coke production because of insufficient O2 and using up

FC fuel because of oxidizing H2 to H2O by remaining O2).

Figure 5 shows the products composition for a fixed oxygen-to-carbon ratio of 0.7 and an incremental STCR. The presence of high steam content dilutes the hydrogen concentration generated from the reformer. This could be due to the fact that, in the presence of high steam content, the strong endothermic steam reforming reaction easily takes place [2], which leads to the low-temperature distribution along the reformer.





3-2-Fuel cell System

The suggested NASA regional jet APU was used as a case study [8]. The SOFC is based on the Gen3 Delphi planar SOFC characteristics. The model of the Solid Oxide Fuel Cell stack has been developed and implemented by the authors in the MATLAB SIMULINK, as described in section 2.

Table 3: Gen 3 SOFC Stack characteristics			
Parameter	Values	unity	
Number of cells	30 cell per stack	-	
active area	105	Cm2	
30 cell Stack weight	13	kg	
30 cell Stack volume	3.5	litter	

3-2-1- Fuel cell System Validation

Figure 6 shows an IV and IP curves from a Generation 3-30-cell stack tested on 48.5% H2. 3%

H₂O, rest N₂. The stack produced 1.53 kW (486 mW/cm) at 570 mA per cm² at 25.5 Volts (0.85 Volts per cell average) at 750° C – 800° C.



Fig. 6: IV and IP curves from a Gen 3 30-cell stack [11]

Fuel cell system model in this study has been evaluated in parameters same as reference [11]. The results are presented in the Figures 7, 8.

By comparing the figure 6 from ref [11] and the results of the simulation in figure 7, 8, the model is validated.

Golnaz Pourabedin et al./ International Journal of Engineering and Technology Sciences (IJETS) 3 (6): 393-407, 2015.



Fig. 8: IV curve from 30 cell model

3-3- SOFC system

A range of SOFC system power outputs between 116 to 185 kW has been established to meet the aircraft minimum and maximum power requirements on the ground and at cruise. Electric power output from the SOFC system is supplied from the SOFC stack. The Balance-Of-Plant in this study includes auto-thermal jet fuel reformer. A computer model for the SOFC was created, and was integrated with balance-of-plant components for system level modeling.

The effect of various parameters on cell performance is studied systematically. The study covers the effect of (a) Steam to Carbon Ratio of the fuel, (b) Reforming Temperature, (c) Excess Air.

Test parameters	Case1	Case2	Case3
mole flow rate (mole/s)	0.1	0.1	0.1
Pressure (atm)	1	1	1
Reforming Temperature (k)	1223	Variable (723 to 1473)	1223
STCR	Variable (1.5 to 4.5)	1.5	1.5
OTCR	0.7	0.7	0.7
Landa (excess air)	1	1	Variable (1 to 4)

Table 4: Input parameters for the base cases

Case1:

The inlet stream consisting of C12H23, H2O and O2 is assumed to enter the reformer at 1223 K with a pressure of 1 atm. In this case STCR changes of 1.5 to 4.5. It is assumed that emissions of the reformer are filtered out before entering the fuel

cell, therefore, just hydrogen and water vapor come into the stack and contributing in reactions. In case 1, the impact of STCR in reforming reaction on the performance of the fuel cell system has been evaluated. Fuel cell power versus current for different STCR is shown in Figure 9.



Fig. 9: Fuel cell power versus current for different STCR

By changing STCR, the input fuel flow rate of the fuel cell is changed (because of increasing hydrogen production). Figures 9, 10 show how the fuel cell power and voltage can be increased by low STCR. As can be seen from figure 9, the amount of fuel cell power can be increased to several hundred watts. In the present model, each cell produces near 150 W. for example, in 275 Amp, low STCR

increases fuel cell power about 430 W and from table 3, the Gen 3 Cell weight is 433 gr. Therefore, it can be seen that by selecting the appropriate STCR, 3 cells is eliminated so system weight is reduced about 1.3 Kg. thus by increasing the product power, a number of cells can be decreased and consequently, fuel cell system weight at the requested power is reduced.



Fig. 10: Fuel cell voltage versus current for different STCR

Therefore, we suggested that to maximize the performance of this ER -SOFC system, low inlet STCR must be applied.

evaluated. In this case temperature changes of 723 to 1473 K. It is assumed that a heat exchanger transforms reformer output temperature to fuel cell operating temperature.

Case2:

In case 2, the impact of reforming temperature on the performance of the fuel cell system is





Fuel cell power versus current for different reforming temperature is presented in Figure 11. Higher output power can be achieved at 1223 K. Under each reforming temperature, there is a critical load current point where the model output power reaches its maximum value. For example, the critical point is 276 A at 1223 K. Beyond these points, load current increasing will reduce the output power due to large ohmic and concentration voltage drops.



Fig. 12: Fuel cell voltage versus current for different temperature

By changing temperature, the input fuel flow rate of the fuel cell is changed (like case 1). Figures 11, 12 show how the fuel cell power and voltage can be increased by high temperature. As can be seen from figure 11, while the temperature is increasing, the amount of fuel cell output power can be increased about a thousand watt. For example, in 275 Amp, high temperature increases fuel cell power about 1241 watt. Therefore, it can be seen that by selecting the appropriate operating temperature, 8 cells is eliminated so system weight is reduced about 3.6 Kg (table 3). Thus by increasing the product power, a number of cells can be decreased and consequently, fuel cell system weight at the requested power is reduced. Excess air is any additional air greater than the theoretical air required to supply a fuel cell stack. It is well known that high operating temperature results in better cell performance, and hence an inordinate excess air flow rate can dramatically reduce the cell performance by lowering the average cell temperature. Therefore, choosing the amount of excess air, resulting in an optimum balance between cell performance and cell durability is critical.

In case 3, the impact of excess air on the performance of the fuel cell system is evaluated. In this case excess air (landa) changes of 1 to 4. The corresponding output power versus current curves at different excess air is shown in Fig. 13.

Case3:



Fig. 13: Fuel cell power versus current for different excess air

As can be seen from figure 13, while the landa is increasing, the amount of fuel cell output power can be increased about several hundred watts. For example, in 275 Amp, fuel cell power is increased about 520 watts by high landa. Therefore, it can be seen that by selecting the appropriate landa, 4 cells is eliminated so system weight is reduced about 1.73 Kg (table 3). Thus by increasing the product power, a number of cells can be decreased and consequently, fuel cell system weight at the requested power is reduced.



Fig. 14: Fuel cell voltage versus current for different excess air

Results indicated that by selecting optimal conditions in each case, the fuel cell system weight is decreased about 6.6 kg (1.5 percent). Therefore,

the Regional Jet aircraft total weight is reduced slightly.

4. Conclusions

The high price of fuel cell technology and the heavy weight of these systems make them not yet competitive with other baseline auxiliary power units, despite their effectiveness. Thus, in order to become competitive, SOFCs should fulfill stringent requirements, both in terms of power-to-weight ratio and in terms of lifetime availability. In order for these systems to become competitive, SOFCs should be developed with a useful life of over 40000 kH and a specific power over 1kW/kg. Therefore, in this study, the simulation of standalone ER-SOFC for aircraft APU allows reducing a global weight of the system about 1.5%. For developing system lifetime, In the future study, the dynamic responses of the model will be investigated.

The simulation of this system for aircraft APU indicated that by increasing the reformer operating temperature and fuel cell excess air, also by low STCR, the system product power increased. Therefore, it can be seen that appropriate balance of plant not only can be developed fuel cell system operating conditions but also reduced system weight.

NOMENCLATURE

α	Number of participating electrons
E _{0,cell}	The reference potential (V).
β	Electron transfer coefficient (0.5)
F	Faraday constant (96487 C/mol)
i ₀	Exchange current (A)
i	Current (A)
R	Gas constant, 8.3143 J/(mol·K)
Р, р	Pressure (Pa)
V	voltage (V) and volume (m ³)
i _{den}	Current density (A/m2)
l_a	Distance from anode surface to the reaction site (m)
l _c	Distance from cathode surface to the reaction site (m)
$D_{i,i}$	Effective binary diffusivity of i-j pair (m ² /s)
T	Temperature (K)
v	Stoichiometric coefficient
d	Chanel Diameter (m)
'n	Molar ratio (mole/sec)
r	Reaction rate
q	Heat/Energy

ch	Conditions at the anode or cathode channel
*	Effective value
cell	Conditions for a single cell
PEN	Conditions for a Positive Electrolyte Negative
Red	Reduction reaction
<i>0x</i>	Oxidation reaction
chem	Chemical
conv	Convective
elec	Electricity
Rad	Radiation

Superscripts and subscripts

References

[1] Braun R J, Gummalla M, Yamanis, J. system architectures for solid oxide fuel cell-based auxiliary power units in future commercial aircraft applications. Journal of Fuel Cell Science and Technology, AUGUST, 2009; 6: 031015-1

[2] Dokmaingam P, Irvine J.T.S, Assabumrungrat S, Charojrochkul S, Laosiripojana N. Modeling of IT-SOFC with indirect internal reforming operation fueled by methane: Effect of oxygen adding as auto thermal reforming. International journal of hydrogen energy, 2010; 35:13271-13279.

[3] Salogni A, Colonna P. Modeling of solid oxide fuel cells for dynamic simulations of integrated systems. Applied Thermal Engineering, 2010; 30: 464–477.

[4] Fuel cell handbook," 6th ed. EG & G Services,Inc., Sci. Appl. Int. Corp. ,DOE, Office FossilEnergy, Nat. Energy Technol. Lab. Morgantown,WV, Nov. 2002.

[5] Stiller C. Design, operation and control modeling of SOFC/GT hybrid systems. Ph.D. thesis, Norwegian University of Science and Technology; 2006.

[6] Ota T, Koyama M, Wen C, Yamada K, Takahashi H. Object-based modeling of SOFC system: dynamic behavior or micro-tube SOFC. Journal of Power Sources, 2003; 118: 430-439. [7] Martinez s. Simulation of Dynamic Operation and Coke-Based Degradation for SOFC-GT-Powered Medium and Long Haul Locomotives. Submitted in partial satisfaction of the requirements for the degree of DOCTOR OF PHILOSOPHY in Mechanical and Aerospace Engineering, 2011.

[8] Mak A, Meier J. Fuel Cell Auxiliary Power Study. Volume 1: RASER Task Order 5, Honeywell Engines, Systems & Services, Phoenix, Arizona, 2007.

[9] Gordon S, McBride B. J. Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. NASA Reference Publication 1311, 1996.

[10] Tornabene R, Wang W Y, Steffen C J, Freeh Joshua E. Development of Parametric Mass and Volume Models for an Aerospace SOFC/Gas Turbine Hybrid System. Paper No. GT2005-68334, ASME TurboExpo 2005, NASA Glenn Research Center, Cleveland, OH, May 2004.

[11] Mukerjee S, Haltiner K, Klotzbach D, Vordonis J, Kerr R, Sprenkle V, Kim J Y, Meinhardt K, Iyer A, Canfield N, Darsell J, Kirby B, Keun Oh T, Maupin J, Voldrich B, Bonnett J. Solid Oxide Fuel Cell Stack for Transportation and Stationary Applications. ECS Transactions, 2009; 25 (2): 59-63.