Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46137

CONCEPTUAL DESIGN AND PERFORMANCE ANALYSIS OF SOFC/MGT HYBRID DISTRIBUTED ENERGY SYSTEM

Zheng Dang
Dept. of Building Environment and Equipment Engineering,
Xi'an Jiaotong University,
Xi'an, Shaanxi 710049, China,
Email:zdang@mail.xjtu.edu.cn

Hua Zhao
Dept. of Building Environment and Equipment Engineering,
Xi'an Jiaotong University,
Xi'an, Shaanxi 710049, China

Guang Xi
National Engineering Research Center of Fluid Machinery and Compressors,
Xi'an Jiaotong University,
Xi'an, Shaanxi 710049, China

ABSTRACT

A numerical model has been developed for the performance analysis of SOFC/MGT hybrid systems with pre-reforming of natural gas, in which a quasi-2 dimensional model has been built up to simulate the cell electrochemical reaction, heat and mass transfer within tubular SOFC. The developed model can be used not only to predict the overall performance of the SOFC/MGT hybrid system but also to reveal the nonuniform temperature distribution within SOFC unit. The effects of turbine inlet temperature (TIT) and pressure ratio (PR) to the performance of the hybrid system have been investigated. The results show that selecting smaller TIT or PR value will lead to relative higher system efficiency and lower CO_2 emission ratio; however this will raise the risk to destroy SOFC beyond the limitation temperature of electrolyte.

INTRODUCTION

Solid oxide fuel cell (SOFC) and micro gas turbine (MGT) hybrid distributed energy system (DES) is a kind of new approach for energy conversion. With the cascaded utilization of chemical energy of fuel, the hybrid system shows the advantages of high efficiency and low emission. Therefore, it should be an important choice for the solution of energy shortage and environment pollution in future. A 220 kW class SOFC/MGT hybrid system developed by Siemens-Westinghouse has ever been demonstrated at the National Fuel Cell Research Center (NFCRC) of the University of California in 2000. Also many researches focused on SOFC/MGT hybrid system have been published elsewhere. However, the research work in this field is still insufficient. Several numerical predicting research works have been done on the performance of hybrid system [1~7]. Most of them used black box model or zero dimension model to treat the fuel cell as a uniform element, which can not predict out the nonuniform temperature distribution within SOFC. This kind of numerical models can not predict out the local thermal spot and thermal stress phenomena occurring during the operation of SOFC. On the other hand, in order to obtain the design basis and control strategy, it's necessary to investigate the effects of configuration parameters on the performance of SOFC/MGT system.

In this paper, a quasi-2 dimensional model is built up for tubular SOFC fueled with natural gas, in which, the calculation for radiation is optimized to improve the predicting accuracy for heat transfer; both CO and H_2 are considered as fuel in the cell electrochemical reactions, and the overpotential model is completed. The predicting model for MGT and the compact regenerator are simplified. Firstly, the developed numerical model is adopted to forecast the performance of SOFC/MGT hybrid systems with pre-reforming of natural gas. Compared the predicting results with the published experimental or simulating data in other literatures, it's verified that the present model is dependable with high precision.

Secondly, the investigations on the parameters of turbine inlet temperature (TIT) and pressure ratio (PR) to the performance of the system have been carried out. A design basis on SOFC/MGT system is concluded. When design a SOFC/MGT hybrid system the first parameter to be ensured is TIT, it means that the first designed component should be MGT and regenerator, then SOFC; and also the area of the design parameters are pointed out, which has taken the efficiency and safety of the system into consideration.

Nomenclature

A	area (m^2)
E	electromotive force (V)
F	Faraday constant, 96485C·mol^{-1}
ΔG	Gibbs free energy change (kW)
P	electric power (kW)
Q	heat transfer rate (kW)
R	gas constant (kJ·kmol^{-1}·K^{-1})
RR	recirculation ratio
SCR	steam to carbon ratio
U	voltage (V)
X	angle coefficient of radiation heat transfer
h	molar enthalpy (kJ·kmol^{-1})
k	reaction rate factor (kJ·kmol^{-1})
$\dot{n}$	molar flow rate (kmol·s^{-1})
p	pressure (Pa)
$\dot{z}_x$	molar flow of reactant x (kmol·s^{-1})
Greek letters	
ε	emissivity
η	efficiency
σ	black body ratiation constant, 5.67 (W·m^{-2}·K^{-4})
Subscripts	
a	anode
aft	air feed pipe
$airc$	air to cathode channel
$airf$	air feed channel
c	cathode
C	compressor
CV	control volume
e	electrolyte
fc	fuel cell
fp	fuel feed pipe
fpc	fuel feed channel
fr	fuel reforming channel
$fuel$	fuel to anode channel
HS	hybrid system
i、j	index of control volume
in	inlet of control volume
out	outlet of control volume
rad	radiation
rw	reforming wall
T	gas turbine
x	reactant

1 SOFC/MGT HYBRID SYSTEM AND NUMERICAL MODEL

Figure 1 shows the schematic layout of a distributed energy system based upon Siemens-Westinghouse 220kW class SOFC/MGT hybrid system. The numerical model will be built up for SOFC, MGT, heat exchanger and combustor respectively. The details will be described in the following sections.

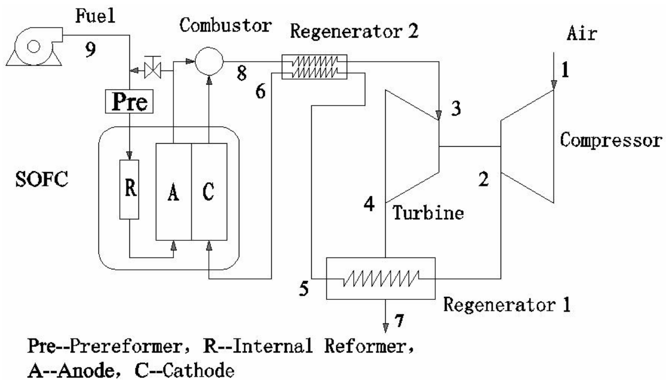

Fig.1 Schematic layout for SOFC/MGT hybrid system

1.1 Mathematical models of SOFC

The SOFC adopted in this paper is a mature tubular SOFC developed by Siemens-Westinghouse. Mathematical models of SOFC include electrochemical model describing the mass transfer, heat transfer model reflecting the energy variation, and loss models representing various irreversible energy losses.

1.1.1 The geometry of SOFC

Figure 2 is the schematic layout of a tubular SOFC. The pre-reformed fuel flows through the fuel feed channel before enters the reforming channel where reforming and shifting reactions occur, and then deliveries to the fuel channel taking part in shifting and electrochemical reactions exporting the electric power. The air is pre-heated in the air feed channel prior to participates in the electrochemical reaction in the air channel.

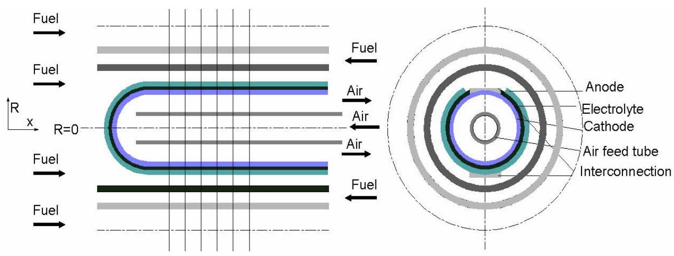

Fig.2 Schematic layout for tubular SOFC

1.1.2 Electrochemical model

Chemical reactions happening in the SOFC fueled by methane are complicated. Reactions occurring in different channels are shown as follows:

In pre-reformer and reforming channel:

Fuel reforming: $CH_4 + H_2O \leftrightarrow CO + 3H_2$ （1）

In pre-reformer, reforming channel and fuel channel:

Steam shifting: $CO + H_2O \leftrightarrow CO_2 + H_2$ （2）

The fuel reforming reaction is slow and highly endothermic, while, the steam shifting reaction is fast and weakly exothermic. The channel of pre-reformer is assumed to be long enough so as to ensure that (1) and (2) are both under chemical equilibrium conditions. The steam shifting reaction is also supposed to be at equilibrium because it is fast. In the reforming channel, (3) is employed to describe the reaction rate of the fuel reforming reaction.

$$\dot{r}_{CH_4} = k_{CH_4} p_{CH_4} \exp(-E_{CH_4} / RT) \qquad (3)$$

Where k_{CH_4} is the reaction rate factor, E_{CH_4} is the activation energy, and p_{CH_4} is the partial pressure of methane.

The amount of steam needed is obtained from the recirculated exhaust gas of SOFC (see in Fig. 1), expressed as the recirculation ratio (RR):

$$RR = \frac{\dot{n}_{CH_4,in}}{\dot{n}_{H_2O,cell\ exit}} SCR \qquad (4)$$

Where SCR is the steam-carbon ratio (SCR).

Owing to the assumption of no volumetric work output, the maximum available power produced by the electrochemical reaction in the SOFC can be expressed as follows:

$$P_{fc,\max} = -\Delta G$$
$$= -(\dot{z}_{CO} \cdot \Delta g_{CO+0.5O_2 \to CO_2} + \dot{z}_{H_2} \cdot \Delta g_{H_2+0.5O_2 \to H_2O}) \qquad (5)$$

The electromotive force of the electrochemical reaction can be written as:

$$E = -\frac{\Delta G}{2(\dot{z}_{CO} + \dot{z}_{H_2})F} \qquad (6)$$

Where $\dot{z}_x$ is the molar flow of x consumed in the electrochemical reaction.

1.1.3 Heat transfer model

As shown in Fig.3, the unit SOFC is discretized into several elements in the axial direction, and then different solid interfaces divide each element into separate control volumes in the radial direction.

Taking one of the control volumes for an example, the below energy conservation equation can be obtained:

$$Q_{CV} + Q_{rad} + \dot{n}_{x,in} h_{x,in} - \dot{n}_{x,out} h_{x,out} - W_{fc} = 0 \qquad (7)$$

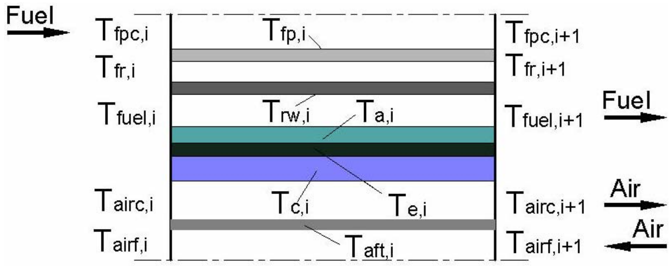

Fig.3 Control volume for energy conservation

Where Q_{CV} are convection and conduction heat transfer, Q_{rad} is the radiative heat transfer, $\dot{n}_{x,in} h_{x,in}$ and $\dot{n}_{x,out} h_{x,out}$ represent the inflow and outflow enthalpy of gas, respectively, and W_{fc} indicates the power exported by the control volume.

The radiative heat transfer in the *i*-th control volume between the reforming wall and the anode can be described by equation (8), and so does the radiative heat transfer between the air feed plate and the cathode.

$$Q_{rad,ra} = \sum \frac{A_{rwi,j}\sigma(T_{rw,j}{}^4 - T_{a,i}{}^4)}{(\frac{1-\varepsilon_{rw}}{\varepsilon_{rw}}) + \frac{1}{X_{j,i}} + \frac{A_{rwi,j}}{A_{ao,i}}(\frac{1-\varepsilon_a}{\varepsilon_a})} \qquad (8)$$

1.1.4 Loss model

Three types of losses are included in a SOFC model: polarization loss, ohmic loss and concentration loss. The concentration loss is neglected in this paper since it is much smaller by comparison with polarization and ohmic loss when the current density is not so high. The empirical equations given by Achenbach [8] are employed for the calculation of the activation polarization loss.

1.2 Mathematical model of MGT

The output power of MGT can be denoted by the following formula:

$$w'_{net} = \eta_T (h_3 - h_4) - (h_2 - h_1) / \eta_{C,s} \qquad (9)$$

Where h_1, h_2, h_3, h_4 are inlet and outlet enthalpy of compressor and turbine, η_T is the internal efficiency of turbine, and $\eta_{C,s}$ is the adiabatic efficiency of compressor. For space reasons, models of circuit and balance-of-plant components are discussed in detail in [9] and [10].

2 RESULTS AND DISCUSSION

2.1 system parameters and validation

Table 1 shows the system parameters and flow inlet conditions for designed configuration. Those data are mainly referred to [11-12].

Table 1 System parameters and flow inlet conditions

parameters	values	parameters	values
Atmospheric air temperature and pressure (℃, atm)	**15, 1**	Pressure ratio	**2.9**
Steam to carbon ratio (SCR)	**2.5**	Compressor adiabatic efficiency (%)	**78**
Fuel utilization factor (%)	**85**	Turbine efficiency (%)	**82**
Air mass flow rate (kg/s)	**0.5897**	Turbine inlet temperature (℃)	**840**
Averaged Current density (A/m^2)	**3200**	Heat exchanger 1 efficiency (%)	**86**
Cell active area (m^2)	**96**	Heat exchanger 2 efficiency (%)	**40**

Compared the simulated results with published performance data for Siemens-Westinghouse 220 kW class SOFC/MGT hybrid system [11, 12] under the conditions listed in Table 1, it is shown that little differences exist in the case of different number of segments used in the calculations. However these differences are very small on cell output voltage, SOFC or MGT output power and system efficiency, which can be found in Table 2. Therefore, it can be concluded that the numerical method developed in present study is valid and reliable.

Table 2 Numerical results of system performance and comparison

Parameters	SW Data	Number of segments		
		5	**10**	**20**
Current density (A/m^2)	**3200**	**3200**	**3200**	**3200**
Cell output voltage (V)	**0.610**	**0.6105**	**0.6102**	**0.6100**
Pressure ratio	**2.9**	**2.9**	**2.9**	**2.9**
Air mass flow rate (kg/s)	**0.5897**	**0.5897**	**0.5897**	**0.5897**
Turbine inlet temperature (℃)	**840**	**840**	**840**	**840**
SOFC dc output power (kW)	**187**	**187.57**	**187.46**	**187.42**
SOFC ac output power (kW)	**176**	**176.32**	**176.22**	**176.17**
MGT ac output power (kW)	**47**	**45.08**	**45.08**	**45.08**
Overall output power (kW)	**223**	**221.40**	**221.30**	**221.25**
System efficiency (%)	**57**	**58.90**	**58.87**	**58.86**
Cell active area (m^2)	**96**	**96**	**96**	**96**

2.2 Parameters effects on system performance

There are two important parameters: one is turbine inlet temperature (TIT) and the other is pressure ratio (PR), which have significant effects on SOFC/MGT system performance. Keeping the flow rate of air and fuel, fuel utilization factor, steam to carbon ratio (SCR), the efficiency of heat exchanger, averaged current density and other system inlet conditions shown in Table 1 constant, when only one of TIT or PR is changed then the influences on system performance can be obtained.

2.2.1 The effects of turbine inlet temperature (TIT)

Figure 5 shows the cell output voltage, output ac power of SOFC, MGT and hybrid system varied with TIT. It can be seen that with increasing turbine inlet temperature the output power of SOFC will decrease; the output power of MGT will increase slightly; the overall output power of hybrid system defined as the sum of the output power of SOFC and MGT will decrease. The cell output voltage will decrease from 0.644 volt to 0.586 volt when TIT is varied from 1073.15K to 1133.15K, which induced the decreasement of SOFC output power. Because the inlet flow rate of fuel is kept constant, the electric generation efficiency of SOFC and thermal efficiency of SOFC/MGT hybrid system will decrease in consequence. Also the emission ratio of CO_2 for per unit of system output power is increased significantly as shown in Fig. 6.

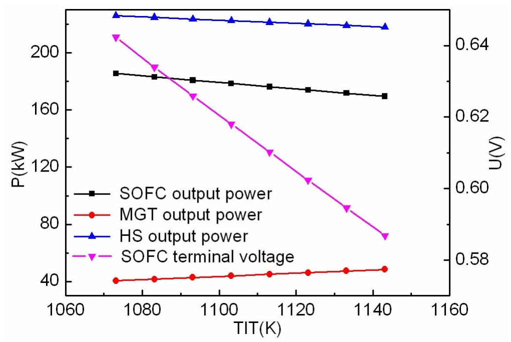

Fig. 5 Output power and cell voltage of SOFC/MGT hybrid system

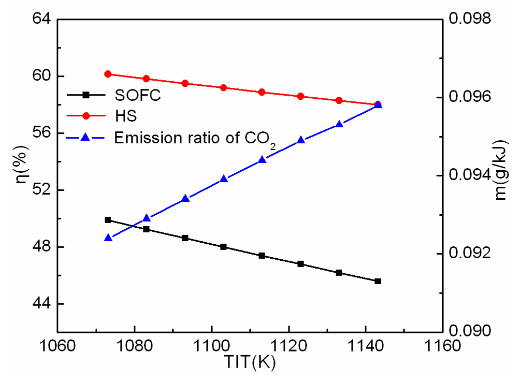

Fig. 6 Efficiency and emission ratio of CO_2 of SOFC/MGT hybrid system

Figure 7 shows the recirculation ratio (RR) and the cell reaction utilization ratio between CO and H_2 (z_{CO}/z_{H_2}) varied with TIT. With increasing turbine inlet temperature recirculation ratio (RR) will increase and z_{CO}/z_{H_2} will decrease also. This is because the shift reaction occurring in the anode channel will turn to the right side. When TIT is increased, the airflow coming into the cathode inlet will obtain smaller heat transfer from heat exchanger 2 located after combustor. Therefore, the temperatures of input air and cell unit will decrease. In consequence, the temperature level in fuel channel will decrease. This will benefit to the shift reaction turning to the right side. Therefore more H_2 will be produced and more CO and H_2O will be consumed. At the exit of anode channel, the steam concentration is lower, to keep the steam to carbon ratio (SCR) constant, the recirculation ratio should be open larger.

Figure 8 shows the electrolyte temperature distribution along the axial direction of tubular SOFC unit. It can be seen clearly that the electrolyte temperatures have the similar distribution shape under different TIT from 1073.15K to 1133.15K. The electrolyte temperature level decreases parallel with TIT increased uniformly. However, the lowering speed is becoming smaller and smaller. That means under lower TIT value, slight variation on TIT will induce big changes on electrolyte temperature level. When TIT is at 1073.15K, the maximum electrolyte temperature is 1307.34K, which is almost close to the permitting limitation value of electrolyte temperature (1323.15K).

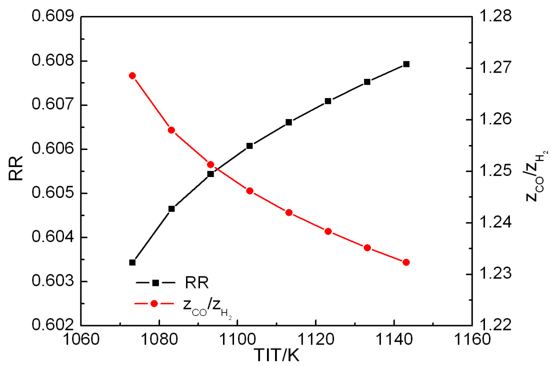

Fig. 7 Recirculation ratio (RR) and z_{CO} / z_{H_2}

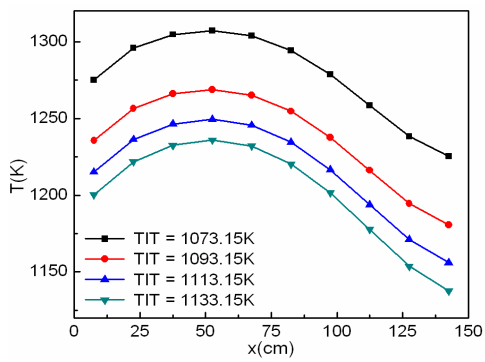

Fig. 8 Electrolyte axial temperature distribution of tubular SOFC unit.

From the former discussion about the effects of TIT on hybrid system, it can be concluded that TIT should be kept as relative lower value in order to get much higher system efficiency and lower CO_2 emission ratio. On the contrary, lower TIT will raise the risk to operate SOFC beyond the electrolyte temperature limit, that means SOFC cell unit will be broken and cease to be effective easily. Therefore, considered about the above two points, it is very important to select an appropriate value of turbine inlet temperature (TIT) for SOFC/MGT hybrid system. In the present study TIT at 1113.15K is well-balanced.

2.2.2 The effects of pressure ratio (PR)

Figure 9 shows the cell output voltage, output ac power of SOFC, MGT and hybrid system varied with pressure ratio (PR). It can be seen that with increasing PR the output power of SOFC will decrease; the output power of MGT will increase slightly; the overall output power of hybrid system defined as the sum of the output power of SOFC and MGT will decrease. The cell output voltage will decrease from 0.632 volt to 0.59 volt when PR is varied from 2.75 to 3.1, which induced the decreasement of SOFC output power while averaged current density is not changed. Because the inlet flow rate of fuel is kept constant, the electric generation efficiency of SOFC and thermal efficiency of SOFC/MGT hybrid system will decrease in consequence. Also the emission ratio of CO_2 for per unit of system output power is increased significantly as shown in Fig. 10.

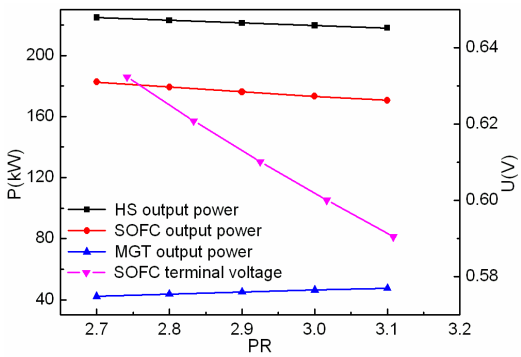

Fig. 9 Output power and cell voltage of SOFC/MGT hybrid system

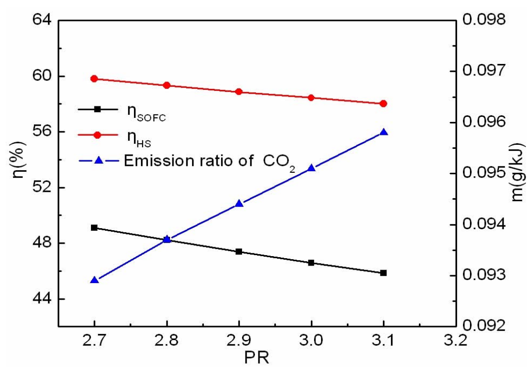

Fig. 10 Efficiency and emission ratio of CO_2 of SOFC/MGT hybrid system

Figure 11 shows the recirculation ratio (RR) and the cell reaction utilization ratio between CO and H_2 (z_{CO}/z_{H_2}) varied with pressure ratio (PR). With increasing PR recirculation ratio (RR) will increase and z_{CO}/z_{H_2} will decrease. This is also because the shift reaction occurring in the anode channel will turn to the right side. When PR is increased and TIT is kept constant, the exhaust temperature of turbine will become lower, that means air to be input into cathode will obtain smaller heat from heat exchanger 1 located after turbine. Therefore the temperatures of input air and cell unit will decrease. In consequence, the temperature level in fuel channel will decrease. This will benefit to the shift reaction turning to the right side. Therefore more H_2 will be produced and more CO and H_2O will be consumed. At the exit of anode channel, the steam concentration is lower, in order to keep the steam to carbon ratio (SCR) constant, the recirculation ratio should be open larger.

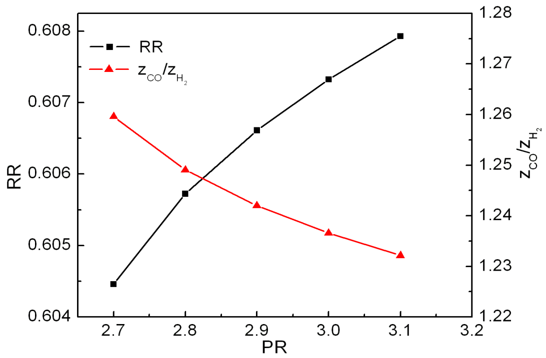

Fig. 11 Recirculation ratio (RR) and the utilization ratio between CO and H_2 (z_{CO}/z_{H_2})

Figure 12 shows the electrolyte temperature distribution along the axial direction of tubular SOFC unit.

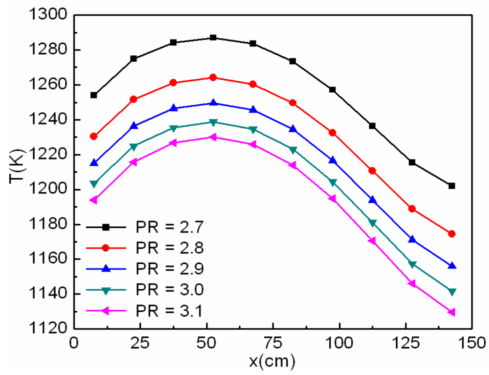

Fig. 12 Electrolyte axial temperature distribution of tubular SOFC unit.

It can be seen clearly that the electrolyte temperatures have the similar distribution shape under different PR from 2.7 to 3.1. The temperature level decreases parallel with pressure ratio increased uniformly. However, the lowering speed is becoming smaller and smaller. That means under lower PR value, slight variation on PR will induce big changes on electrolyte temperature level. When PR is at 2.7, the maximum electrolyte temperature is about 1290K, which is almost close to the permitting limitation value of electrolyte temperature (1323.15K).

From the above discussion about the effects of pressure ratio (PR) on hybrid system, it can be concluded that PR should be kept at relative lower value in order to get much higher system efficiency and lower CO_2 emission ratio. On the contrary, lower PR will raise the risk to operate SOFC beyond the electrolyte temperature limit, that means SOFC cell unit will be broken and cease to be effective easily. Therefore, considered about the above two points, it is very important to select an appropriate value of pressure ratio (PR) for SOFC/MGT hybrid system. In the present study PR at 2.9 is well-balanced.

3 CONCLUSIONS

A numerical model has been developed for the performance analysis of SOFC/MGT hybrid systems with pre-reforming of natural gas, in which a quasi-2 dimensional model has been built up to simulate the cell electrochemical reaction, heat and mass transfer within tubular SOFC. The developed model can be used not only to predict the overall performance of the SOFC/MGT hybrid system but also to reveal the nonuniform temperature distribution within SOFC unit. Compared the simulation results with published data, it's verified that the present model is dependable with high precision.

The effects of turbine inlet temperature (TIT) and pressure ratio (PR) to the performance of the hybrid system have been investigated. It is found that selecting smaller TIT or PR value will lead to relative higher system efficiency and lower CO_2 emission ratio; however this will raise the risk to destroy SOFC beyond the limitation temperature of electrolyte. Therefore, for a configuration design of SOFC/MGT hybrid system it is very important to select appropriate values of turbine inlet temperature and pressure ratio. Meanwhile, it is also indicated that the traditional models such as black box model or zero dimension model used in the performance predicting of SOFC/MGT hybrid system are quite insufficient. Because those models only treat the fuel cell as a uniform element and can not predict out the nonuniform temperature distribution within SOFC. Therefore, they can not show the risk of broken the SOFC accurately.

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China (50976092) and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry of China 2008.

REFERENCES

[1] P. Aguiar, D.J.L. Brett, N.P. Brandon, 2008, "Solid Oxide Fuel Cell/Gas Turbine Hybrid System Analysis for High-altitude Long-endurance Unmanned Aerial Vehicles," International Journal of Hydrogen Energy, **33**, pp. 7214-7223.

[2] A. Musa, M.D. Paepe, 2008, "Performance of Combined Internally Reformed Intermediate/High Temperature SOFC Cycle Compared to Internally Reformed Two-staged Intermediate Temperature SOFC Cycle," International Journal of Hydrogen Energy, **33**, pp. 4665-4672.

[3] T. Araki, T. Taniuchi, D. Sunakawa, etc., 2007, "Cycle Analysis of Low and High H2 Utilization SOFC/Gas Turbine Combined Cycle for CO2 Recovery," Journal of Power Sources, **171**, pp. 464-470.

[4] P. Lisbona, L.M. Romeo, 2008,"Enhanced Coal Gasification Heated by Unmixed Combustion Integrated with an Hybrid System of SOFC/GT," International Journal of Hydrogen Energy, **33**, pp. 5755~5764.

[5] S.H. Chan, O.L. Ding, 2005,"Simulation of a Solid Oxide Fuel Cell Power System Fed by Methane," International Journal of Hydrogen Energy, **30**, pp.167-169.

[6] S.H. Chan, H.K. Ho, Y. Tian, 2003, "Modelling for Part-load Operation of Solid Oxide Fuel Cell-Gas Turbine Hybrid Power Plant," Journal of Power Sources, **114**, pp. 213-227.

[7] S.K. Park, K.S. Oh, T.S. Kim, 2007, "Analysis of the Design of a Pressurized SOFC Hybrid System Using a Fixed Gas Turbine Design," Journal of Power Sources, **170**, pp.130–139.

[8] E. Achenbach, 1994, "Three-dimensional and Time–dependent Simulation of a Planar Solid Oxide Fuel Cell Stack," Journal of Power Sources, **49**, pp. 333-348.

[9] H. Zhao, 2010, "Performance Analysis of the SOFC/MGT Hybrid Distributed Energy System," Degree thesis, Xi'an Jiaotong University, Xi'an, China.(in Chinese)

[10] H. Zhao, Z. Dang, G. Xi, 2010, "The Investigation of the Coupling Characters of SOFC/MGT Hybrid System," presented at the Annual Academic Conference of Chinese Society of Engineering Thermophysics, Nov.7~10, Nanjing, China. (in Chinese)

[11] T.W. Song, J.L. Sohn, J.H. Kim, et al., 2005, "Performance Analysis of a Tubular Solid Oxide Fuel Cell/Micro Gas Turbine Hybrid System Based on a Quasi-two Dimensional Model," Journal of Power Sources, **14**2, pp. 30-42.

[12] R.A. George, 2000, "Status of Tubular SOFC Field Unit Demonstrations," Journal of Power Sources, **86**, pp. 134-139.