Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 158 (2006) 361–367
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Performance characteristics of a MW-class SOFC/GT hybrid system based on a commercially available gas turbine

Tae Won Song [a], Jeong Lak Sohn [a,*], Tong Seop Kim [b], Sung Tack Ro [a]

[a] School of Mechanical and Aerospace Engineering, Seoul National University, San 56-1 Shilim-Dong, Gwanak-Gu, Seoul 151-742, Republic of Korea
[b] School of Mechanical Engineering, Inha University, 253 Yonghyun-Dong, Nam-Gu, Incheon 402-752, Republic of Korea

Received 13 September 2005; received in revised form 24 September 2005; accepted 27 September 2005
Available online 14 November 2005

Abstract

The ultimate purpose of a SOFC/GT hybrid system is for distributed power generation applications. Therefore, this study investigates the possible extension of a SOFC/GT hybrid system to multi-MW power cases. Because of the matured technology of gas turbines and their commercial availability, it was reasonable to construct a hybrid system with an off-the-shelf gas turbine. Based on a commercially available gas turbine, performance analysis was conducted to find the total appropriate power for the hybrid system with consideration of the maximum allowable cell temperature. In order to maintain high performance characteristics of the hybrid system during part-load operations, it was necessary to find the optimal control strategy for the system according to the change in power required. The results of the performance analysis for part-load conditions showed that supplied fuel and air must be changed simultaneously. Furthermore, in order to prevent performance degradation, it was found that both cell temperature and turbine inlet temperature must be maintained as close as possible to design-point conditions.

Keywords: Solid oxide fuel cell; Gas turbine; Hybrid system; Performance analysis; Design-point condition; Part-load operations

1. Introduction

For various applications, such as in electric power generation, the solid oxide fuel cell (SOFC) is expected to be one of the most promising future power sources because of its high efficiency and ultra low emission. It has been theoretically proven that a SOFC-based hybrid power system combined with a gas turbine might provide higher efficiency than the SOFC alone [1]. Despite various proposals for system configurations and prototype tests during the last several years, SOFC/GT hybrid systems have only been developed for kW-class power generations [2–4]. However, as indicated in the Vision 21 Technology Roadmap announced by the Department of Energy, USA in 1999, a SOFC/GT hybrid system will ultimately be developed for commercial entry into multi-MW distributed generation applications [5]. To apply a SOFC/GT hybrid system to large power generations, the amount of power generated by both the SOFC and gas turbine must be increased. In general, increasing the number of unit cells and/or substack modules can raise the SOFC power. With the exception of its size, there are no dramatic changes in the SOFC configuration with an increased generated power. However, the configurations and operating characteristics of gas turbines vary greatly with generated power. For example, a micro gas turbine (MGT), which is generally defined as a gas turbine generating multi-kW power, has a simple radial-type rotor and changes to the rotating speed control its power. On the other hand, a multi-MW gas turbine generally has a complex, axial-type rotor, which rotates at a constant speed despite the load condition. The generated power of the multi-MW gas turbine is controlled by changing the amount of supplied air through manipulation of the inlet guide vanes located in front of the compressor inlet. In addition to dissimilar power generation methods, the design features of the two types of gas turbines are quite different. In general, two important design parameters of a gas turbine, the values of the pressure ratio and turbine inlet temperature, rise with increases in generated power, thus improving the turbine efficiency.

Although the hybrid system is advantageous, there are many practical problems to overcome so that an improved performance can be obtained. The most important concern is the smooth matching of a SOFC module with a gas turbine. Typically, the

* Corresponding author. Tel.: +82 2 880 7434; fax: +82 2 889 6205.
E-mail address: jlsohn@snu.ac.kr (J.L. Sohn).

0378-7753/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2005.09.031

gas turbines for the theoretically optimal design of a hybrid system may not be available as off-the-shelf items. Therefore, it is more practical to design a hybrid system by using a commercially available gas turbine that best fits the intended system. In this design procedure, an important issue is the optimal matching between a chosen gas turbine and a SOFC module. The items to be matched include: operating temperatures, pressures and operating strategies. This study sought to examine the matching of these aspects by systematic analysis. This study extended previous research on the performance analysis of a multi-hundred kW-class SOFC/MGT hybrid system [6] to the MW-class system. The present study was based on a commercially available MW-class gas turbine developed by Solar Turbines, Mercury 50, and a tubular SOFC module from Siemens-Westinghouse. Lundberg et al. [7] studied the possible configuration of a MW-class SOFC/GT hybrid system using the same gas turbine. They chose the cost of electricity (COE) as the parameter to find the optimal power of the hybrid system. In contrast, the present study considered the maximum allowable cell temperature as a limiting parameter in the determination of system power. Additionally, operating characteristics at part-load conditions are discussed.

2. System configurations

Mercury 50, shown in Fig. 1, was selected as the commercially available gas turbine for the construction of the MW-class SOFC/GT hybrid system because of its high efficiency and high performance recuperator. This turbine began to be commercially available in December 2003, having completed more than 40,000 h of operation at field evaluation sites in the United States, France, and Australia [8]. Lundberg et al. [7] fully described the modification of the structure of Mercury 50 to fit the hybrid system. Mercury 50 has a nominal power rating of 4.6 MW, a heat rate of 8863 Btu kWh^{-1}, an efficiency of 38% at ISO conditions of a 9.9 pressure ratio, and a turbine inlet temperature of 1130 °C. Its exhaust gas temperature and airflow rate are 379 °C and 17.78 kg s^{-1}, respectively. The performance evaluation of Mercury 50, based on its up-to-date specifications, was conducted in the present study by computational analysis and

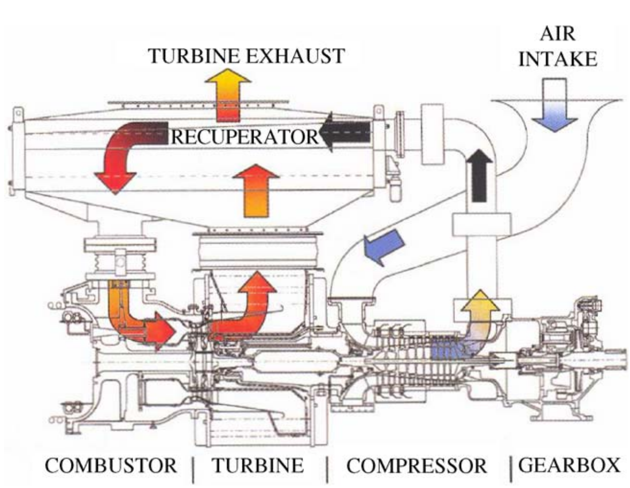


Fig. 1. Constructions and flow paths in the Mercury 50 gas turbine [5].

Table 1
Specifications of the Mercury 50 gas turbine: results of the performance analysis based on published data

Descriptions	Published data [4,5]	Predicted value
Compressor		
10 stage axial compressor		
Pressure ratio	9.90	
Isentropic efficiency (%)	86.00[a]	
Air flow rate (kg s^{-1})	17.80	17.60
Exit temperature (°C)	N/A	318.52
Combustor		
Annular type		
Fuel flow rate (kg s^{-1})	0.25	0.25
Exit pressure (kPa)	N/A	944.07
Exit temperature (°C)	1160.00[a]	
Turbine		
2 stage axial turbine		
Turbine rotor inlet temperature (°C)	1130.00[a]	
Isentropic efficiency (%)	86.00[a]	
Exit temperature (°C)	N/A	640.00
Exit pressure (kPa)	N/A	107.28
Recuperator		
Primary surface type	Primary surface	
Effectiveness (%)	92.00	
Gas-stream		
Exit temperature (°C)	374.00	368.36
Exit pressure (kPa)	N/A	105.18
Air-stream		
Exit temperature (°C)	N/A	614.29
Exit pressure (kPa)	N/A	973.27
System		
Electric power generated (MW)	4.60	4.60
Electric generation efficiency (%)	38.50	38.22

[a] Modified values based on published data [7,8].

is summarized in Table 1. The results showed that the computational analysis was reasonably accurate in predicting electric generation efficiency. In addition, predictions were made for some important features that were not found in published data, such as air stream temperature and pressure at the exit of the recuperator.

The SOFC part considered in this study was based on the concept of multiple SOFC substack modules as described in Lundberg et al. [7]. Each substack module, as shown in Fig. 2, was composed of the following: 576 tubular SOFCs; steam reforming devices for the supplied fuel (methane); and a combustion zone for the effluent gas from the tubular SOFCs. Each tubular SOFC had a length of 1500 mm and a diameter of 22 mm. Increasing the number of multiple substacks could modularly raise the SOFC power. Fig. 3 represents a schematic diagram of the MW-class SOFC/GT hybrid system considered in this study. The basic concept of the hybrid system configuration, which is a combination of the pressurized SOFC module and a recuperated gas turbine, was similar to the concept of the kW-class system configuration described in previous works [1–4,6]. The system performance of the hybrid system could be improved by supplying additional fuel to the combustor located in front of the

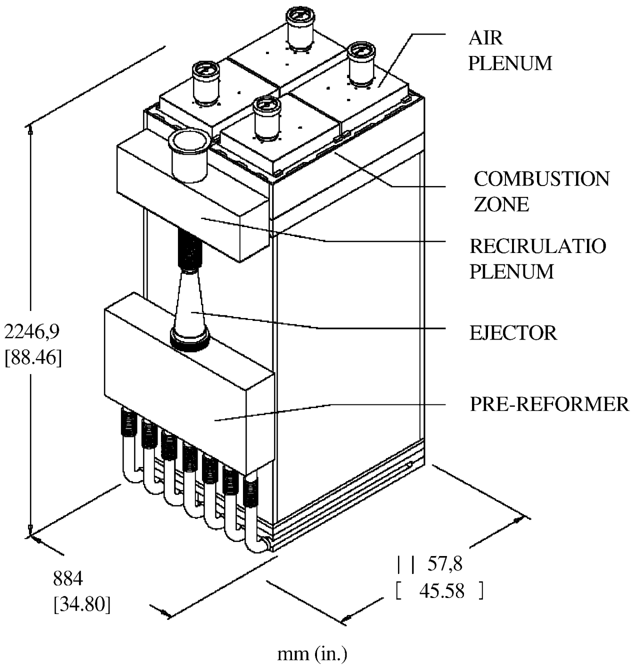


Fig. 2. Constructions of a SOFC substack module [4].

turbine, since the turbine inlet temperature of a MW-class gas turbine was generally higher than the cell temperature of the SOFC module. This combustor also played an important role in part-load operations, as discussed later.

3. Studies for determination of the system specifications

Since Mercury 50 was selected as the gas turbine, the total power of the hybrid system depended on the power of the SOFC module. Increasing the SOFC power, whose efficiency was higher than that of the gas turbine, could raise the system efficiency; although, other issues might restrict the system power. As previously described, Lundberg et al. [7] found that the optimal power of the hybrid system occurs at the minimum electricity cost. The cost of electricity decreases with the increase in SOFC power; this is a direct response to the improvement of the system efficiency. However, in spite of continuous increase in the system efficiency, additional SOFC power no longer reduces the cost of electricity. This result is closely related to the increase in installation cost with additional SOFC power. With the same gas turbine as selected in this study, Lundberg et al. [7] determined the optimal power of the hybrid system to be 12.5 MW with an efficiency of nearly 60% (Net AC/LHV).

Alternatively, in this study, the power was determined by using the maximum cell temperature of the tubular SOFCs as a limiting parameter. All fuel cells must be operated at conditions that maintain the cell temperatures below the maximum allowable temperature. Due to its relation to component durability, the cell temperature is a very important parameter to control during operation for high fuel cells such as a SOFC. In the present study, the maximum allowable temperature was set to 1020 °C, corresponding to the temperature set in Lundberg et al. [7].

For the selection of the amount of power, the performance of the SOFC/GT hybrid system shown in Fig. 3 was analyzed with the data of the selected gas turbine described in Table 1 and with different numbers of SOFC substacks. For the performance analysis of the SOFC/GT hybrid system, a computational tool based on a quasi-two-dimensional model developed by Song

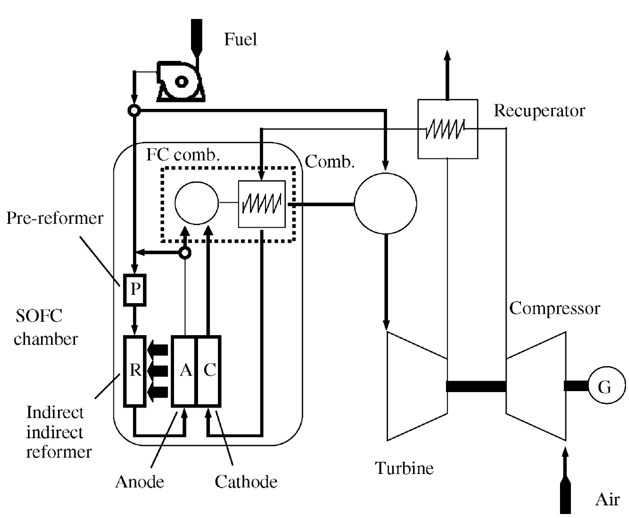


Fig. 3. Schematic diagram of the MW-class SOFC/GT hybrid system.

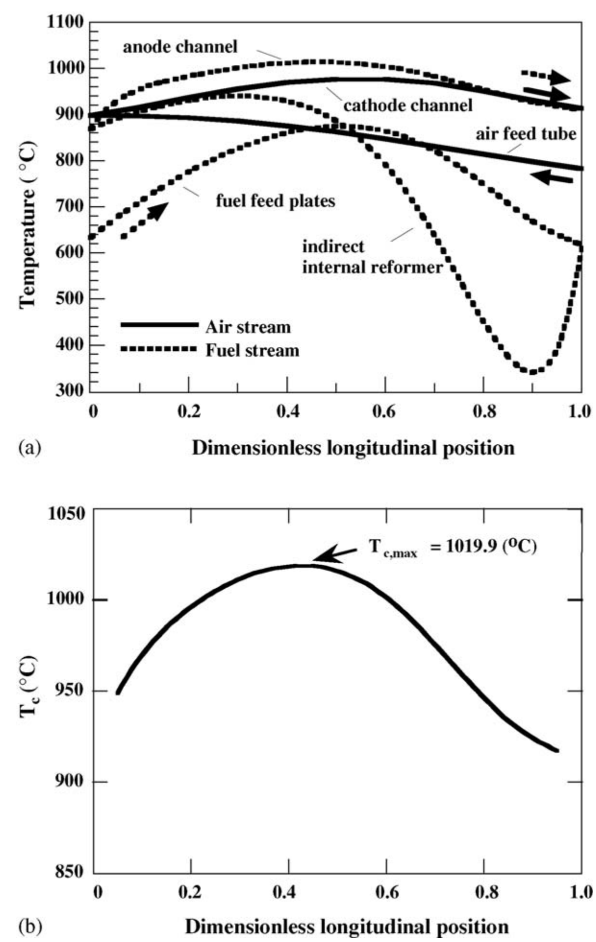


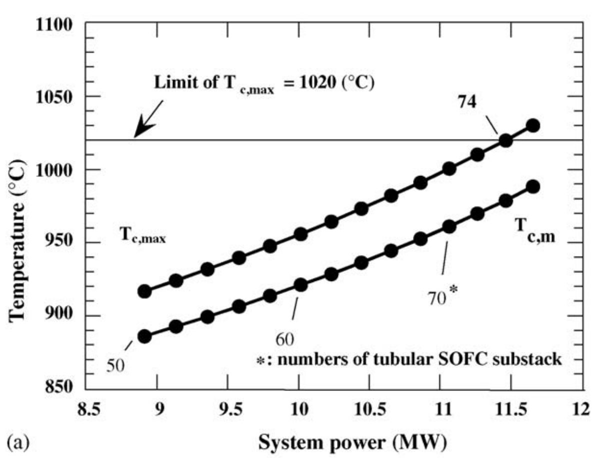
Fig. 4. Temperature distributions along the longitudinal direction of the SOFC substack module in the SOFC/GT hybrid system with a net system AC power of 11.462 MW: (a) various flow streams and (b) cell temperature.

et al. [6] was used. This tool can predict the performance of a SOFC/GT hybrid system with local temperature distributions along the longitudinal direction on the inside of a tubular.

3.1. SOFC substack module

Fig. 4 represents the predicted local temperature distributions of various flow streams inside a SOFC substack module. It was clearly shown that temperature distributions were closely related to the complex physical phenomena. For example, the endothermic reforming reaction inside the indirect internal reformer and the exothermic electrochemical reaction inside the tubular SOFCs contributed to the dramatic change along the longitudinal direction of the SOFC temperatures. The combination of heat generation by electrochemical reaction and the heat transfer from the fuel cell to the reformer moved the maximum cell temperature to approximately the middle of the longitudinal direction of the tubular SOFCs.

As shown in Fig. 5, the predicted maximum cell temperature and system efficiency were raised proportionally to the system power increases. Since the air supply was fixed by the selected gas turbine, this rise was caused by the reduction of the air supply to each tubular SOFC with the increase in number of SOFC substacks. The system power was selected at the condition where the predicted maximum cell temperature, 1019.9 °C in Fig. 5, was not higher than the maximum allowable temperature. The limiting temperature was not the mean cell temperature, but a local peak value that was higher than the mean value. Although increasing system power can increase the system efficiency, it was still limited by the maximum allowable cell temperature of the SOFC module. Based on the selected condition, the total system power was chosen to be 11.462 MW at a system efficiency of 58.3%.



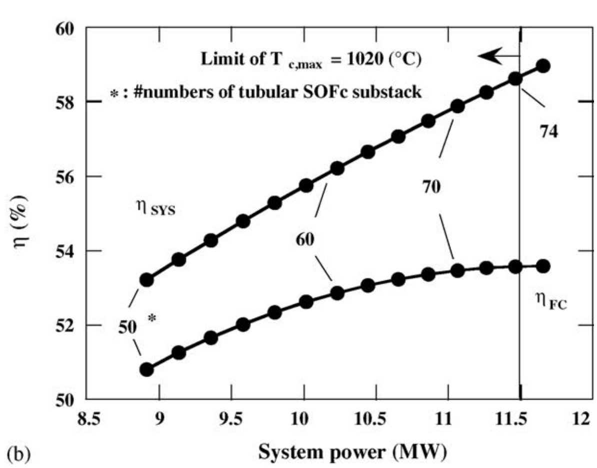


Fig. 5. Performance characteristics of the SOFC/GT hybrid system with the change of total system power: (a) maximum cell temperature and (b) system efficiency.

Table 2
Specifications of the selected SOFC/GT hybrid system based on a Mercury 50 gas turbine that was considered in this study

Parameter	Descriptions	Value
Given data	Current density ($A\,m^{-2}$)	3000
	Cell voltage (V)	0.69
	Fuel utilization factor	0.85
	Pressure ratio	9.90
	Air flow rate ($kg\,s^{-1}$)	17.60
	TIT (°C)	1160
	LHV_{CH_4} ($kJ\,kg^{-1}$)	50019
Predicted values	Maximum cell temperature (°C)	1019.9
	Fuel flow rate	
	Total ($kg\,s^{-1}$)	0.391
	SOFC ($kg\,s^{-1}$)	0.261
	GT ($kg\,s^{-1}$)	0.130
	Air-utilization factor	0.23
	SOFC	
	DC power (MW)	7.358
	AC power (MW)	6.990
	GT AC power (MW)	4.674
	Net AC power (MW)	11.462
	SOFC efficiency[a] (%)	53.57
	System efficiency[b] (%)	58.62

[a] SOFC efficiency = $\dot{W}_{FC}/(\dot{m}_{f,FC}LHV_{CH_4})$.
[b] System efficiency = $\dot{W}_{SYS}/(\dot{m}_{f,SYS}LHV_{CH_4})$.

The performance data that was predicted at the selected condition, described in Table 2, represented the design-point conditions of the MW-class SOFC/GT hybrid system based on the Mercury 50 gas turbine with consideration of the maximum allowable cell temperature. In comparison with the power ratio of the kW-class cases described in Veyo et al. [3], the power ratio of the SOFC module and the gas turbine of the system considered in this study was considered to be very low. This result was due to the limitation of the SOFC power by the maximum allowable cell temperature. Also, it is important to note that due to the temperature difference between the fuel stream at the exit of the SOFC module and that at the inlet of a turbine there was a significant amount of fuel supplied to the gas turbine, that is, to the combustor located in front of a turbine.

4. Behaviors of the part-load performance

When the power demand from the SOFC/GT hybrid system is reduced, the system must be operated at part-load conditions;

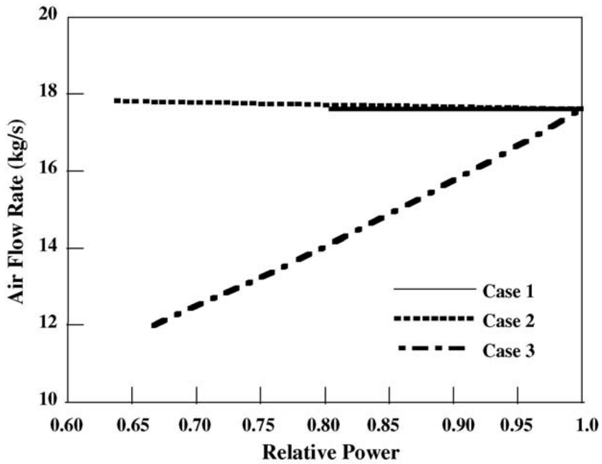


Fig. 6. Changes to the amount of supplied air at part-load conditions.

consequently, the amount of supplied fuel must be reduced. In both the SOFC and gas turbine, a reduction of generated power by the decrease of supplied fuel also caused an efficiency drop. In the case of the SOFC, the efficiency drop at the part-load condition with a reduction to the supplied fuel was closely related to the decrease of cell temperature. Alternatively, a reduced fuel supply to the gas turbine decreased the turbine inlet temperature. As a result, it influenced the performances of both the compressor and the turbine by accelerating the efficiency drop of the gas turbine at the part-load condition. Therefore, in the combined SOFC and gas turbine system described in Fig. 3, it was necessary for the values of the cell temperature and the turbine inlet temperature to be maintained as high as possible during part-load operations to minimize the deterioration of system performance.

Another important parameter that can be controlled at part-load operating conditions is the amount of air supplied to the system. With the simultaneous reduction of supplied air and fuel,

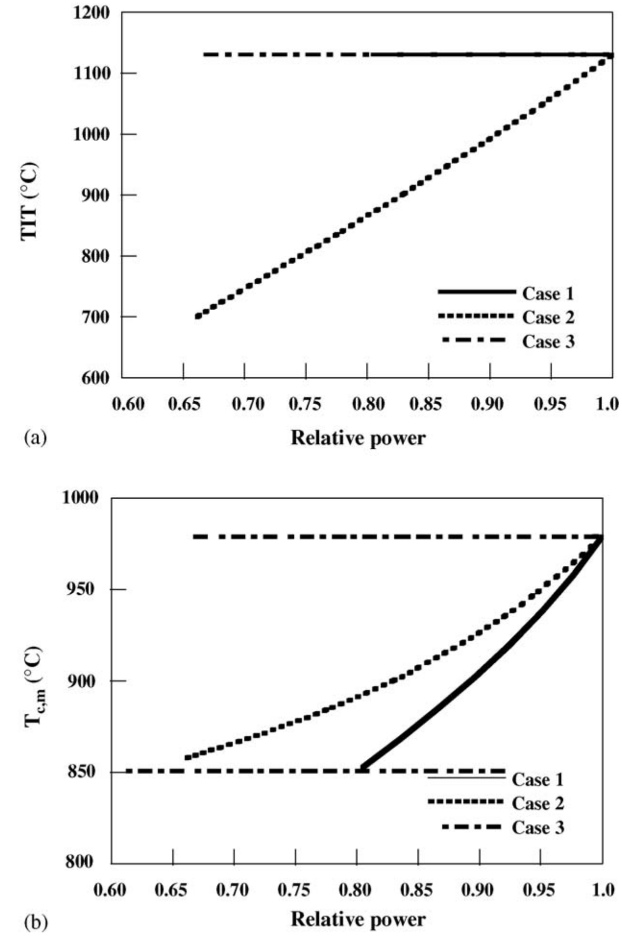


Fig. 8. Changes to mean cell and turbine inlet temperatures at part-load conditions: (a) turbine inlet temperature and (b) mean cell temperature.

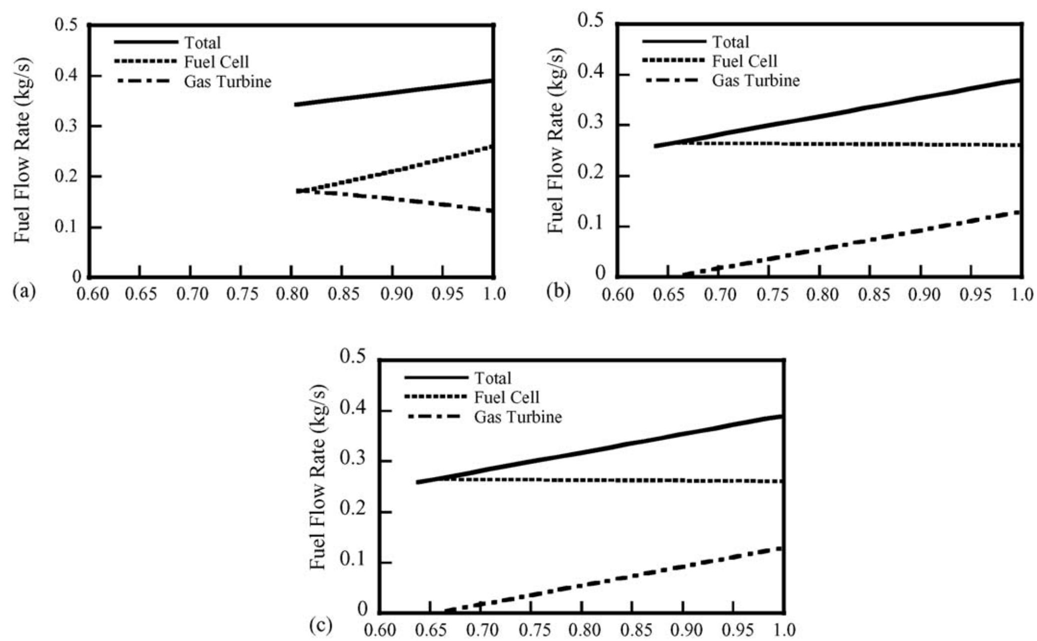


Fig. 7. Changes to the amount of supplied fuel at part-load conditions: (a) Case 1: ($\dot{m}_{FC}$ control); (b) Case 2: ($\dot{m}_{GT}$ control); (c) Case 3:($\dot{m}_{air}$ control).

it was possible to sustain cell and turbine inlet temperatures at the design-point condition temperatures, respectively. This was possible because of the minimum changes of the air-utilization ratio in the SOFC and the air–fuel ratio in the gas turbine. In the SOFC/GT hybrid system shown in Fig. 3, the pressurization process in the compressor of the gas turbine supplied air. Therefore, due to the operating characteristics at a constant rotating speed for the part-load conditions described above, for a selected multi-MW class gas turbine, the amount of air supplied to the system can only be controlled by adjusting the angles of the inlet guide vanes (IGVs) located in front of the compressor inlet.

In the present study, three operation strategy cases for part-load operations of the hybrid system were considered: two strategies involved the reduction of the supplied fuel without a change of supplied air and one strategy involved the simultaneous reduction of both the supplied fuel and air. Details of each operating strategy are described as follows:

Case 1 ($\dot{m}_{FC}$ control): Reduction of the supplied fuel to the SOFC module.
Case 2 ($\dot{m}_{GT}$ control): Reduction of the supplied fuel to the gas turbine.
Case 3 ($\dot{m}_{air}$ control): Simultaneous reduction of both supplied fuel and air to the system.

The performance of the MW-class hybrid system at part-load conditions was analyzed on the basis of the selected system specifications summarized in Table 2. The same computational tool used for the performance prediction of the system at the design-point condition in the previous section was used with modifications. These modifications allowed prediction of part-load performance characteristics of gas turbines with the change of the angles of IGVs as described in Kim et al. [9].

Figs. 6 and 7 show the results of performance analysis of the system at part-load conditions. In all three cases, the amount of supplied air and fuel varied with the reduction of the required power. In regard to the power reduction, for Cases 1 and 2 the amount of supplied air was maintained at approximately the same value as the design-point; however, it was reduced proportionally with the decreased power in Case 3. As shown in Fig. 7(a), for Case 1, additional fuel was supplied to the gas turbine with the reduction of power generation. This case described the operation of the gas turbine at its design-point performance during part-load operations and showed a constant turbine inlet temperature with the change of produced power, as shown in Fig. 8(a). However, as shown in Fig. 8 (b), because of the limitation of the amount of additional fuel supplied to the SOFC module with the reduction of $\dot{m}_{GT}$, the cell temperature could not be sustained as a constant value at part-load conditions. On the other hand, due to the simultaneous control of supplied air and fuel to the system in Case 3, both cell temperature and turbine inlet temperature could be maintained as constant values at part-load conditions (refer to Fig. 8 (a and b)). Another important finding from Figs. 7 and 8 was that the range of the part-load operations in Case 1 was much narrower than those of the other two cases.

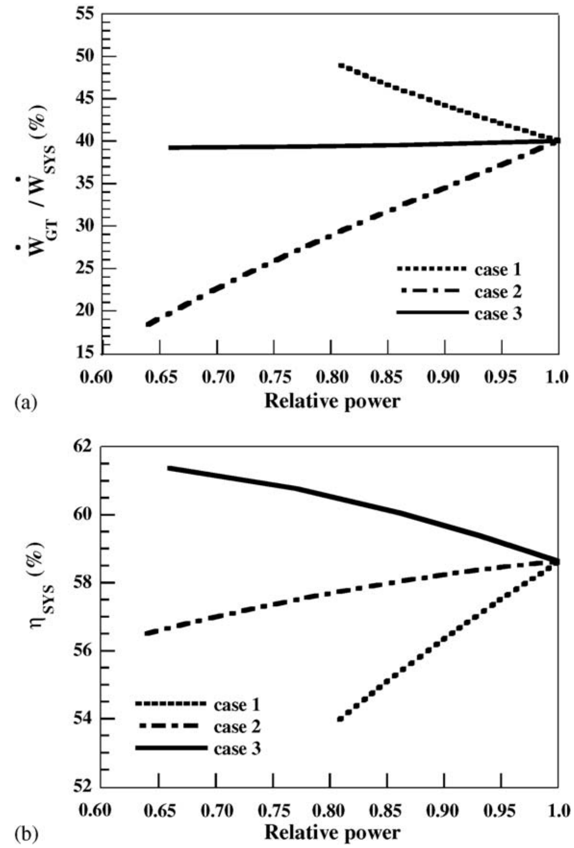


Fig. 9. System performance characteristics at part-load conditions: (a) ratio of produced power by a gas turbine to total system power and (b) system efficiency.

Fig. 9(a) shows that for Case 3 the ratio of $\dot{W}_{GT}/\dot{W}_{sys}$ was maintained at a constant value for part-load conditions due to the simultaneous reduction of the power produced by both the gas turbine and the SOFC module. Additionally, in Case 3, the system efficiency was enhanced with the reduction of generated power, which means that the slope of power reduction at part-load conditions was lower than that of the change in supplied fuel. Similar results were also observed for part-load operations in cases of kW-class hybrid systems with variable rotating speed controls of a micro gas turbine described in Campanari [10].

5. Conclusions

The performance of the multi-MW class hybrid system was analyzed to investigate the possible extension of the SOFC/GT hybrid system concept for large power generations. A commercially available gas turbine, 4.6 MW Mercury 50 from Solar Turbines, was selected as the gas turbine for the MW-class hybrid system. The results of the analysis showed that the maximum allowable cell temperature of the SOFC module limited the size of the total power generation of the hybrid system; this limitation reduced the benefits of the efficiency rise by the increased SOFC power. Based on the selected gas turbine, the total system power and efficiency were predicted to be 11.5 MW and 58.62%, respectively.

The performance analysis results for part-load conditions showed that the simultaneous changes of both supplied fuel and air by manipulating IGV angles could sustain both cell and turbine inlet temperatures at those of the design-point condition; consequently, these changes improved the performance characteristics with the reduction of produced power. The performance characteristics of the multi-MW class hybrid system with controlled IGV angles considered in this study were very similar to those of the multi-kW system with a variable rotating speed of the gas turbine.

References

[1] A.F. Massardo, F. Lubelli, Internal reforming solid oxide fuel cell-gas turbine combined cycles (IRSOFC-GT). Part A: Cell model and cycle thermodynamic analysis, Trans. ASME: J. Eng. Gas Turbine Power 122 (2000) 27–35.

[2] S.E. Veyo, L.A. Shockling, J.T. Dederer, J.E. Gillett, W.L. Lundberg, Tubular solid oxide fuel cell/gas turbine hybrid cycle power systems: status, Trans. ASME J. Eng. Gas Turbine Power 124 (2002) 845–849.

[3] S.E. Veyo, S.D. Vora, K.P. Litzinger, W.L. Lundberg, Status of pressurized SOFC/gas turbine power system development at Siemens Westinghouse, ASME Paper GT2002-30670, 2002.

[4] K.P. Litzinger, S.E. Veyo, L.A. Shockling, W.L. Lundberg, Comparative evaluation of SOFC/gas turbine hybrid system options, ASME Paper GT2005-68909, 2005.

[5] Vision 21 Technical Roadmap, National Energy Technology Laboratory, Department of Energy, USA, 1999.

[6] T.W. Song, J.L. Sohn, J.H. Kim, T.S. Kim, S.T. Ro, K. Suzuki, Performance analysis of a tubular solid oxide fuel cell/micro gas turbine hybrid power system based on a quasi-two dimensional model, J. Power Sources 142 (2005) 30–42.

[7] W.L. Lundberg, S.E. Veyo, M.D. Moeckel, A high-efficiency solid oxide fuel cell hybrid power system using the Mercury 50 advanced turbine systems gas turbine, ASME J. Eng. Gas Turbine Power 125 (2003) 51–58.

[8] Mercury 50 Recuperated, Modern Power Syst., March 2004, pp. 36–37.

[9] J.H. Kim, T.W. Song, T.S. Kim, S.T. Ro, Model development and simulation of transient behavior of heavy duty gas turbines, J. Eng. Gas Turbines Power 123 (3) (2001) 1–6.

[10] S. Campanari, Full load and part-load performance prediction for integrated. SOFC microturbine systems, ASME J. Eng. Gas Turbine Power 122 (2000) 239–246.