Available online at www.sciencedirect.com
ScienceDirect
Journal of Power Sources 166 (2007) 155–164
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Performance characteristics of a solid oxide fuel cell/gas turbine hybrid system with various part-load control modes

Jin Sik Yang, Jeong L. Sohn *, Sung Tack Ro

School of Mechanical and Aerospace Engineering, Seoul National University, San 56-1, Shilim-Dong, Gwanak-Gu, Seoul 151-742, Republic of Korea

Received 19 September 2006; received in revised form 14 December 2006; accepted 14 December 2006
Available online 18 January 2007

Abstract

The purpose of this study is to compare the part-load performance of a solid oxide fuel cell/gas turbine (SOFC/GT) hybrid system in three different control modes: fuel-only control, rotational speed control, and variable inlet guide vane (VIGV) control. While the first mode maintains a constant air supply and reduces the supplied fuel to achieve part-load operation, the other modes are distinguished by the simultaneous controls of the air and fuel supplied to the system. After the performance analysis of a SOFC/GT hybrid system under part-load operating conditions, it was concluded that the rotational speed control mode provided the best performance characteristics for part-load operations. In spite of worse performance than the rotational speed control mode, the VIGV control mode can be a good candidate for part-load operation in a large-scale hybrid system in which the rotational speed control is not applicable. It was also found that, in spite of a relatively small contribution to the total system power generation, the gas turbine plays an important role in part-load operation of a SOFC/GT hybrid system.

Keywords: Solid oxide fuel cell; Gas turbine; Hybrid system; Part-load performance; Efficiency; Power

1. Introduction

Solid oxide fuel cells (SOFCs) are promising power generation devices for various applications. Their high-temperature characteristics provide both high thermal efficiency and a high-temperature exhaust gas, which can be used as a source of heat or for additional power generation. SOFC technology has continuously evolved during the last several decades. After the successful development of a SOFC-based cogeneration system by Siemens–Westinghouse, which used its commercially available tubular SOFC [1], research efforts were extended to the development of SOFC/gas turbine (GT) hybrid systems [2,3]. The basic aim of the SOFC/GT hybrid system is to enhance the thermal efficiency of a SOFC-based power system by combining it with a gas turbine as the bottoming cycle.

The role of a gas turbine in a SOFC/GT hybrid system is to use the high-temperature exhaust gas of the SOFC to: (1) produce additional electrical power and (2) supply air to the SOFC. Siemens–Westinghouse developed a 220 kW-class SOFC/GT hybrid system in the early 2000s and also proposed hybrid systems with different power classes [3,4]. The National Energy Technology Laboratory (NETL) and the National Fuel Cell Research Center (NFCRC) led the American effort to develop SOFC/GT hybrid systems [5–8]. Concerns regarding the hybrid system were extended to fuel cell companies, such as Rolls–Royce, with their valuable recent progress [9,10]. FuelCell Energy has successfully applied the hybrid concept to its MCFC-based power system [11,12].

Following the successful development of a 220 kW-class SOFC/GT hybrid system for distributed power generation, it is desirable to extend the concept to large-scale power systems, such as multi-MW class systems, in the future. For this purpose, Siemens–Westinghouse already studied the possible applications of the SOFC/GT hybrid system based on a commercially available gas turbine for large-scale power generation [13].

Power generation systems, including the SOFC/GT hybrid system, usually operate best at a specific design condition, but must also operate well under conditions that vary from the specific design condition. In the case of the SOFC/GT hybrid system, its part-load efficiency is strongly influenced by the gas turbine. In general, the performance of a gas turbine is rapidly

* 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
doi:10.1016/j.jpowsour.2006.12.091

Nomenclature

A	area (m^2)
C	heat capacity ($W K^{-1}$)
C_p	isobaric specific heat ($W kg^{-1} K^{-1}$)
C_r	the ratio of heat capacities
F	Faraday constant (96,485 $C mol^{-1}$)
G	reduced air flow rate (Fig. 4)
j	current density ($A m^{-2}$)
LHV	lower heating value ($kJ kg^{-1}$)
$\dot{m}$	mass flow rate ($kg s^{-1}$)
N	rotational speed (rpm)
NTU	the number of transfer units
P	pressure (Pa)
PR	pressure ratio
TIT	turbine inlet temperature (°C)
U	overall heat transfer coefficient ($W m^{-2} K^{-1}$)
U_a	air utilization factor
U_f	fuel utilization factor
V	voltage (V)
ΔV	voltage loss (V)
$\dot{W}$	power (kW)
$\dot{z}$	molar flow rate ($kmol s^{-1}$)

Greek letters

ε	effectiveness of heat exchanger
η	efficiency

Subscripts

a	air
act	activation loss
c	cell or compressor
comp	compressor
d	design point
f	fuel
FC	fuel cell
GT	gas turbine
HS	hybrid system
i	chemical species
max	maximum
min	minimum
oc	open-circuit
ohm	ohmic loss
turb	turbine

reduced at part-load conditions, which, as a result, governs the part-load efficiency of the entire SOFC/GT hybrid system. For the part-load operation of a multi-hundred kW-class SOFC/GT hybrid system, two kinds of control modes, namely, the fuel-only control mode and rotational speed control mode, were proposed in previous studies [14,15]. It was concluded that the rotational speed control mode could provide better performance than the fuel-only control mode [14,15]. Here, the fuel-only control mode involves manipulating the fuel supply to reduce the generated power while maintaining constant air supply. On the other hand, the rotational speed control mode involves control of the supplied air by manipulation of the rotational speed of the gas turbine. In this case, the supplied fuel must also be manipulated to maintain the same fuel–air ratio as that at the full-load condition.

In the case of a gas turbine, the rotational speed control mode is only applicable to small gas turbines that have high speed alternators and inverters capable of producing electric power at various rotational speeds. The rotational speed control mode cannot be applied to the multi-MW class large-scale gas turbines because they typically use gear boxes and synchronous generators that require constant rotational speed for all load conditions. In this class of gas turbines, the variable inlet guide vane (VIGV) control mode is commonly used instead of the rotational speed control [16]. The role of the VIGV, which is installed in front of a compressor, is simply to control the amount of air supplied to the gas turbine operating at a constant rotational speed. The VIGV control mode can also be applied to small-scale gas turbines if they need to be operated at a constant rotational speed at part-load conditions.

The control modes of a gas turbine at part-load conditions strongly impact the overall performance of a SOFC/GT hybrid system. The purpose of this paper is to study the influence of three kinds of part-load control modes, as described above, on the performance of a SOFC/GT hybrid system. For this purpose, these three control modes were applied to a 220 kW-class SOFC/GT hybrid system, and its part-load performance characteristics were investigated.

2. System configurations

Fig. 1 shows the schematic diagram of the 220 kW-class SOFC/GT hybrid system considered in this study. Its specifications at the design-point condition are summarized in Table 1, which are quoted from the results of a previous study [17]. The supplied fuel (methane) is reformed at both the pre-reformer and the indirect internal reformer before it enters the anode side of the SOFC stack. The required heat and steam for the steam reforming reactions in the pre-reformer are provided by recirculating part of the anode off-gas. Here, the amount of recirculated

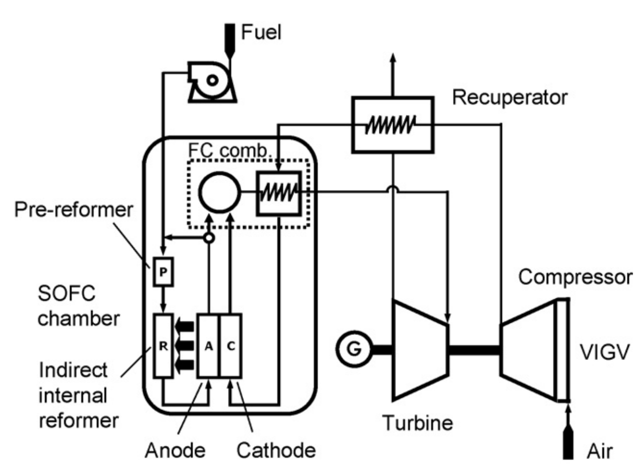

Fig. 1. Schematic diagram of the SOFC/GT hybrid system.

Table 1
Specifications of the SOFC/GT hybrid system considered in Fig. 11

Parameter	Value
Hybrid system	
Ambient conditions (°C, atm)	15.0, 1.0
System power (kW)	220.0
SOFC	
Steam–carbon ratio	2.5
Fuel utilization factor	0.85
Average current density ($A\,m^{-2}$)	3200.0
Fuel inlet temperature (°C)	15.0
Gas turbine	
Pressure ratio	2.9
Turbine inlet temperature (°C)	840.0
Compressor efficiency (%)	78.0
Turbine efficiency (%)	82.0
Recuperator effectiveness (%)	89.0

off-gas is a function of the steam–carbon ratio tolerable to the SOFC stack. Part of the heat generated from the electrochemical reactions in the SOFC stack is transferred to the indirect internal reformer. In the present study, the amount of this heat is determined by assuming a constant cell temperature of the SOFC stack. Air is pressurized by a compressor, which is driven by a turbine, and is then heated by a recuperator and supplied to the cathode side of the SOFC stack.

Residual anode off-gas is mixed and burned with cathode off-gas in a combustor and the high-temperature exhaust gas is supplied to the turbine for power generation. The exhaust gas from the turbine is used to warm up the supplied air in a recuperator.

Fig. 2 represents the schematic diagram of the recuperated gas turbine, which is the same type as the gas turbine adopted in the SOFC/GT hybrid system shown in Fig. 1. This is composed of a centrifugal compressor, radial turbine, combustor, and recuperator.

The SOFC-only system shown in Fig. 3 refers to the part described as the "SOFC chamber" in Fig. 1, which is a combination of SOFCs and their related reforming units. All processes, such as the reforming reactions, the electrochemical reactions, heat transfer, gas flow, and so on, in the SOFC-only system are the same as those in the hybrid system.

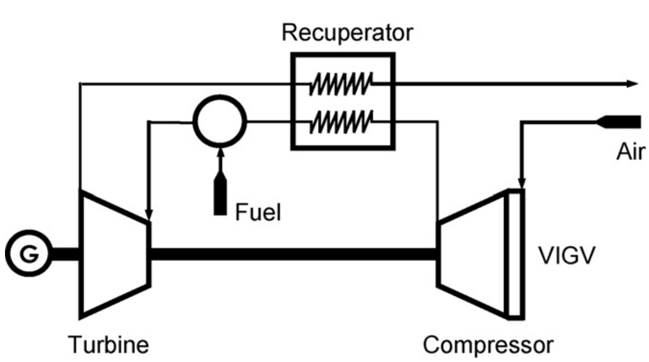

Fig. 2. Schematic diagram of the recuperated gas turbine.

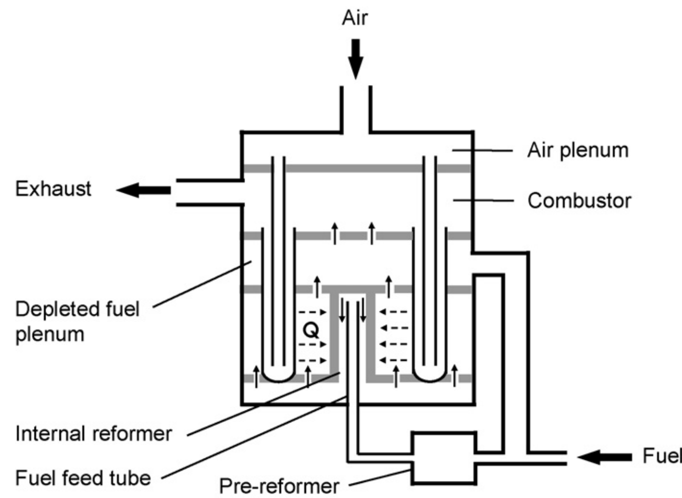

Fig. 3. Schematic diagram of the SOFC-only system.

3. Mathematical models and concepts of control modes

The generated power and thermal efficiency of the SOFC/GT hybrid system considered in this study can be calculated as follows:

$$\dot{W}_{HS} = \dot{W}_{FC} + \dot{W}_{GT} \quad (1)$$

$$\eta_{HS} = \frac{\dot{W}_{HS}}{\dot{m}_f (LHV)_f} \quad (2)$$

with

$$\dot{W}_{FC} = V_c j A_c \quad (3)$$

and

$$\dot{W}_{GT} = \dot{W}_{turb} - \dot{W}_{comp} \quad (4)$$

On the other hand, the thermal efficiency of the SOFC-only system is described below

$$\eta_{FC} = \frac{\dot{W}_{FC}}{\dot{m}_f (LHV)_f} \quad (5)$$

As noted in Eqs. (2) and (5), the thermal efficiencies of both the hybrid and SOFC systems are defined based on the lower heating value of the supplied fuel.

The reforming and electrochemical reactions considered in this study are as follows:

- Reforming reactions:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (6a)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (6b)$$

- Electrochemical reactions:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (7a)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (7b)$$

The supplied fuel is reformed to hydrogen and carbon monoxide by steam reformations such as fuel reforming reaction of methane and water–gas shifting reaction of carbon monoxide (Eq. (6b)) in the pre-reformer, the internal reformer, and the anode of the SOFC. The reforming reactions are assumed to occur under chemical equilibrium conditions. In particular, both the steam reforming and the electrochemical reactions occur in the anode chamber at the same time. Both hydrogen and carbon monoxide introduced from the internal reformer take part in the electrochemical reactions in the anode, and unreformed methane in the internal reformer and part of carbon monoxide are reformed to hydrogen in the anode of the SOFC.

The current density of the fuel cell can be expressed as a function of the fuel consumed by the electrochemical reactions:

$$j = \frac{2F\dot{z}}{A_c} = \frac{2F(\dot{z}_{H_2} + \dot{z}_{CO})}{A_c} \tag{8}$$

To calculate the power generated by the fuel cell (Eq. (3)), under the assumption of negligible concentration losses in the range of the current density considered in this study, the cell voltage can be obtained according to the calculation below

$$V_c = V_{oc} - (\Delta V_{act} + \Delta V_{ohm}) \tag{9}$$

Here, for the calculation of the activation and ohmic losses, the same mathematical models described in Song et al. [17] were used in this study.

The part-load operation of a SOFC/GT hybrid system means that the system is operated at a power level lower than the power generated at its design-point condition. The power of a SOFC can be reduced mainly by reducing the amount of supplied fuel. Under the assumption of a constant fuel utilization factor (U_f) at part-load operating conditions, the consumed fuel by a SOFC is proportional to supplied fuel as follows:

$$\dot{z} = U_f \dot{m}_f \tag{10}$$

The reduction of supplied fuel to the SOFC decreases the fuel consumption and then, reduces the current density. Another important parameter at part-load operation of a SOFC is the air utilization factor (U_a) which strongly influences the cell temperature. On the other hand, in the case of a gas turbine, its generated power is mainly proportional to the amount of supplied air. Also, the fuel–air ratio, which is closely related to the turbine inlet temperature, is another important parameter related to part-load operation of a gas turbine. Therefore, for part-load operation of a SOFC/GT hybrid system, it is very important to consider performance characteristics according to different control strategies for the supplied fuel and air.

The recuperator shown in Figs. 1 and 2 play an important role in preheating the air supplied to the system. Its effectiveness significantly influences the system efficiency and can be calculated by the effectiveness-NTU method during off-design operation of the hybrid system, which is defined as

$$\varepsilon = \frac{1 - \exp[(C_r - 1)\mathrm{NTU}]}{1 - C_r \exp[(C_r - 1)\mathrm{NTU}]} \tag{11}$$

where

$$\mathrm{NTU} \equiv \frac{\mathrm{UA}}{C_{min}} \tag{12}$$

and

$$C_r \equiv \frac{C_{min}}{C_{max}} \tag{13}$$

Here, the number of transfer units (NTU) is a dimensionless parameter widely used for heat exchanger analysis. The C_{min} and C_{max} mean the heat capacities of the cold and hot gas streams, respectively, entering the recuperator. During part-load operation, these heat capacities are dependent on the temperature and species of each stream as shown in the following equation:

$$C = \sum_i [\dot{m}\, C_p(T)]_i \tag{14}$$

Therefore, the changes of both the temperatures and compositions of gas streams directly influence the recuperator effectiveness. The decrease in the air flow rate has a predominant role in enhancing the recuperator effectiveness because the overall heat transfer coefficient U can be expressed as a function of the air flow rate.

If the amount of supplied fuel is reduced during part-load operation under the fuel-only control mode, the SOFC power will be decreased due to reduction of electrochemical reactions in the SOFC. In addition, reduced fuel also influences the cell temperature, which is the most important parameter related not only to the SOFC power but also to the power generated by the entire SOFC/GT hybrid system. Low cell temperature decreases the turbine inlet temperature and therefore, reduces power generation and thermal efficiency of the gas turbine. The decrease in turbine inlet temperature reduces the turbine expansion capability and decreases the gas turbine's performance because of the link between the compressor and the turbine.

To minimize the efficiency loss caused by reduction of the supplied fuel, the simultaneous reduction of both the supplied air and fuel is commonly adopted, as briefly described above. If the amount of supplied air can be reduced by keeping the same fuel-air ratio as that at the full-load condition to maintain the cell temperature as high as possible, the efficiency loss of the SOFC can be minimized. This strategy also helps to minimize the drop in the turbine inlet temperature, which is closely related to the gas turbine's performance.

For reduction of the supplied air to the SOFC/GT hybrid system in Fig. 1, two kinds of control modes are considered in this study: the reduction in the rotational speed of the gas turbine (*i.e.*, rotational speed control mode) and the reduction in the air-entering area of the compressor inlet by the change in the VIGV angles (*i.e.*, VIGV control mode). These control modes require a careful consideration of the impact on the compatibility between the compressor and turbine. In the case of the SOFC/GT hybrid system, since operation of the gas turbine depends on the operational characteristics of the SOFC, it is necessary to ascertain whether the turbine inlet temperature obtained from the compressor and turbine characteristic maps is compatible with the temperature of the hot gas exhausted from the SOFC chamber.

These temperatures, therefore, can be matched by manipulating the fuel flow rate.

As well-known from gas turbine theory, manipulating the rotational speed for reduction of the air supplied to a gas turbine changes both the pressure ratio and the isentropic efficiency of a compressor. In the VIGV control mode, it also changes the performance characteristics of the compressor. The influence of the change of compressor performance on the gas turbine operation can be determined by the compatibility analysis described in Saravanammuttoo et al. [18]. In this study, the performance analyses of the SOFC/GT hybrid system in Fig. 1 at part-load operating conditions were conducted by solving the mathematical models described above and analyzing the compatibility of a gas turbine. For simplicity, it is assumed in this study that the fuel utilization factor, defined as the ratio of the fuel consumed by the SOFC to the fuel supplied to the system, is constant for all control modes.

4. Results and discussion

4.1. Part-load performance characteristics of the gas turbine

Prior to the performance analysis of the SOFC/GT hybrid system, the performance characteristics of the two independent subsystems, the gas turbine and the SOFC-only system, are investigated. For the performance analysis of the recuperated gas turbine as shown in Fig. 2, the performance characteristics of both the compressor and the turbine at part-load conditions are needed. For this purpose, the performance characteristic curves of a centrifugal compressor and a radial turbine developed by Zhang and Cai [19] were adopted. The influence of the VIGV angles on the compressor performance was calculated by the method described in Kim [20] and their results are shown in Fig. 4, which represent deviations of the compressor performance according to different VIGV angles. These results show that the VIGV angles significantly influence the parameters related to compressor performance.

Fig. 5 represents the result of the performance analysis of the gas turbine shown in Fig. 2 for three different part-load control modes. In the case of the fuel-only control mode, the turbine inlet temperature decreases rapidly with reduced power, and this decrease is the main cause of the efficiency drop at part-load conditions. Efficiency drop in the fuel-only control mode becomes more severe as the rotational speed decreases. On the other hand, in the case of the rotational speed control mode, it is possible to minimize the decrease in thermal efficiency within a certain range of reduced power conditions if the turbine inlet temperature is maintained at the same value as that at the full power condition. In the VIGV control mode case, the performance degradation of the gas turbine at part-load operational conditions is larger than that in the rotational speed control mode, but smaller than that in the fuel-only control mode. It is interesting to note from Fig. 6 that both the rotational speed control and VIGV control modes are useful for the reduction of the supplied air at part-load operation of the gas turbine. The smallest fuel consumption in the rotational speed control mode at part-load

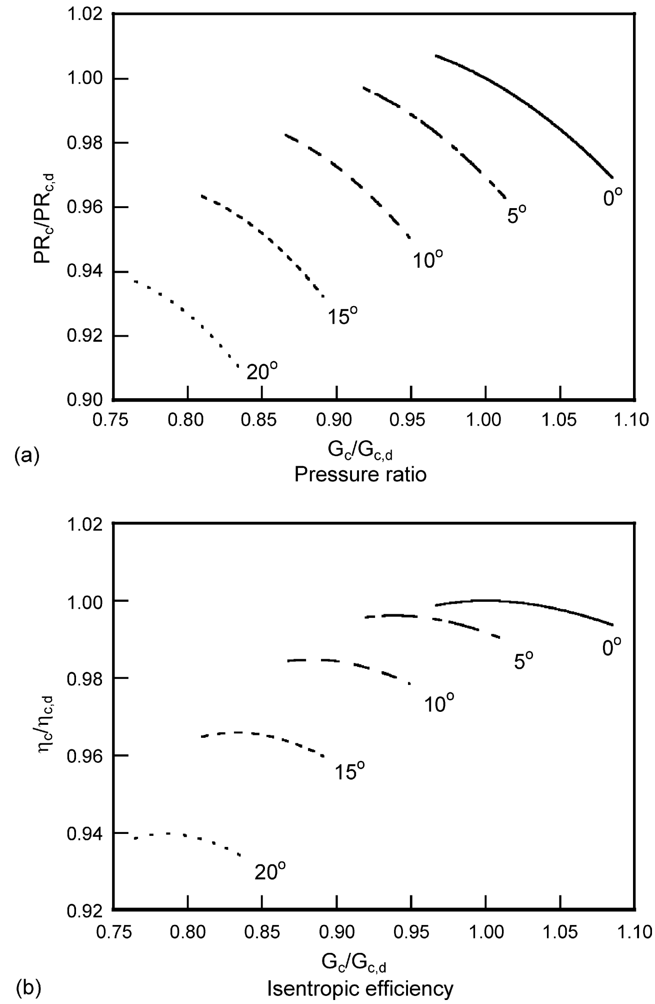

Fig. 4. Performance characteristics of the centrifugal compressor in the gas turbine with different VIGV angles.

conditions is related to the high thermal efficiency of the gas turbine as shown in Fig. 5. Fig. 7 represents the operating paths of a compressor for three different control modes. In spite of the similar patterns of the decreasing pressure ratio due to two

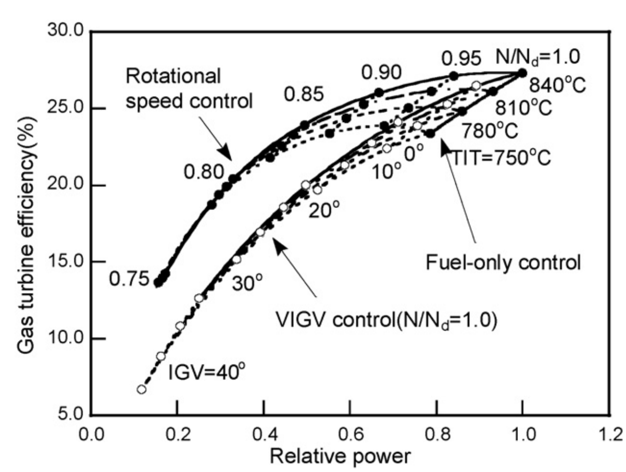

Fig. 5. Thermal efficiency of the recuperated gas turbine at part-load operating conditions.

air/fuel control strategies at part-load operations, the compressor's isentropic efficiency in the rotational speed control mode is higher than that in the VIGV control mode and therefore, the former shows better efficiency than the latter. In the case of the fuel-only control mode, in spite of the high pressure ratio and isentropic efficiency of the compressor, the rapid drop in turbine inlet temperature, as shown in Fig. 8, results in large gas turbine efficiency drop at part-load conditions.

4.2. Performance characteristics of the SOFC-only system

Next, the part-load performance of the SOFC-only system described in Fig. 3 is investigated. For this purpose, two kinds of options to control power production are considered in this study: fuel-only control and air/fuel control modes. In the case of the fuel-only control mode, the amount of supplied fuel is reduced as the same air supply as that at the full power condition is maintained. On the other hand, an air/fuel control mode, which is equivalent to the rotational speed control and VIGV control modes in a gas turbine, means the reduction of supplied air simultaneously with the reduction of supplied fuel. In this case, the air utilization factor, defined as the ratio between the consumed and supplied air, is assumed to be constant during

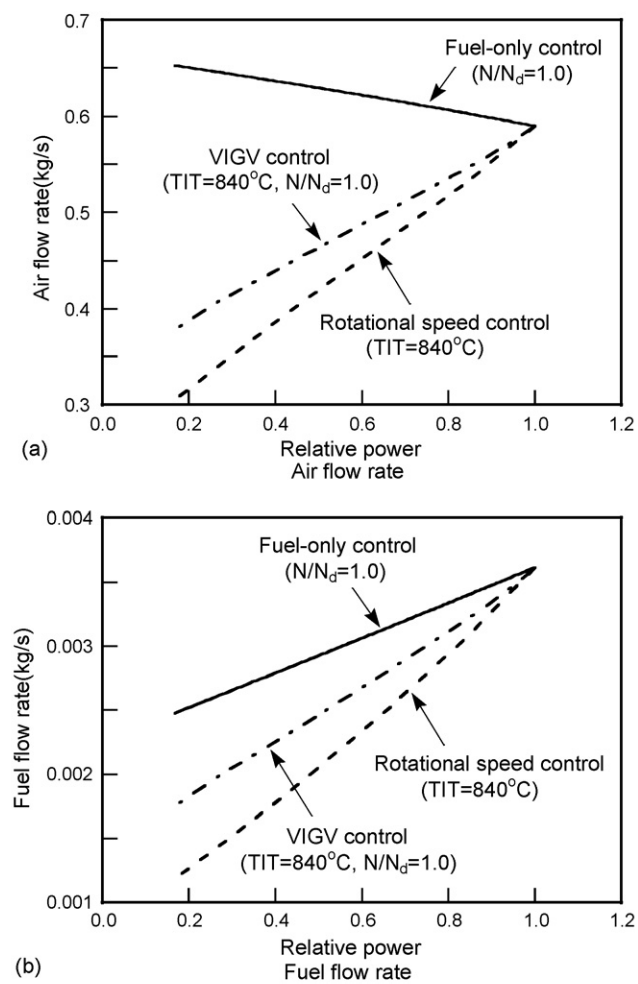

Fig. 6. Air and fuel flow rates at part-load conditions of the recuperated gas turbine.

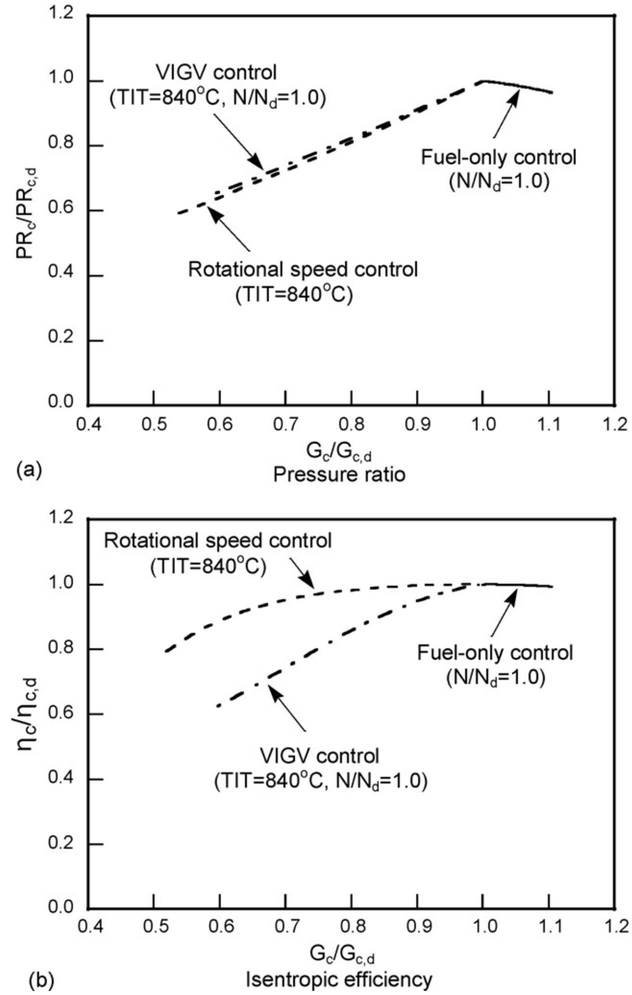

Fig. 7. Operating lines of the centrifugal compressor in the gas turbine with three different part-load control modes.

part-load operations. Also, to maintain the same operating concept as that in the hybrid system, the exhaust temperature of the SOFC-only system at part-load conditions is the same as that at the full power condition as shown in Fig. 9(a). The lower

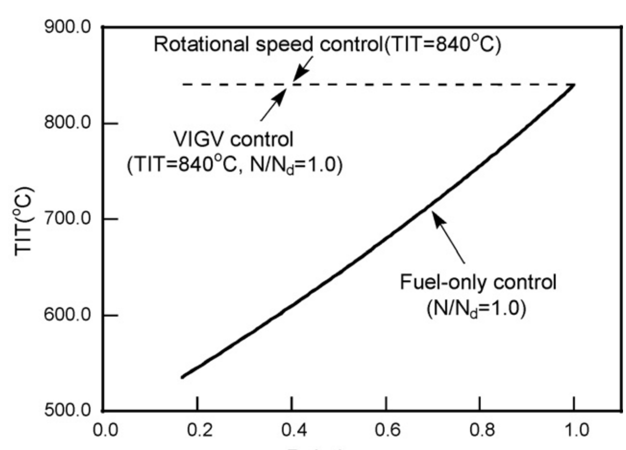

Fig. 8. Turbine inlet temperature of the recuperated gas turbine at part-load operating conditions.

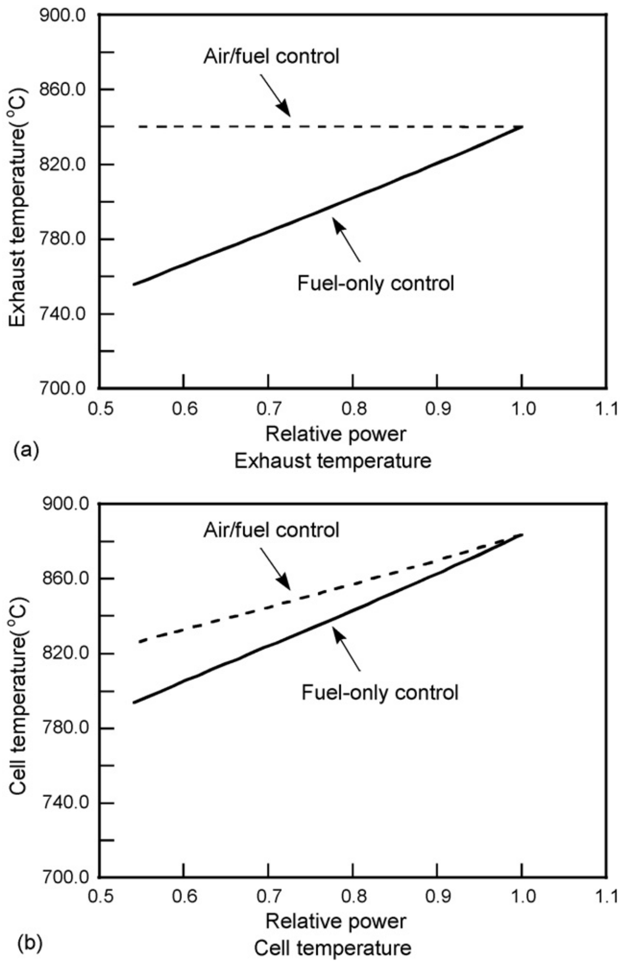

Fig. 9. Exhaust and cell temperatures of the SOFC-only system at part-load operating conditions.

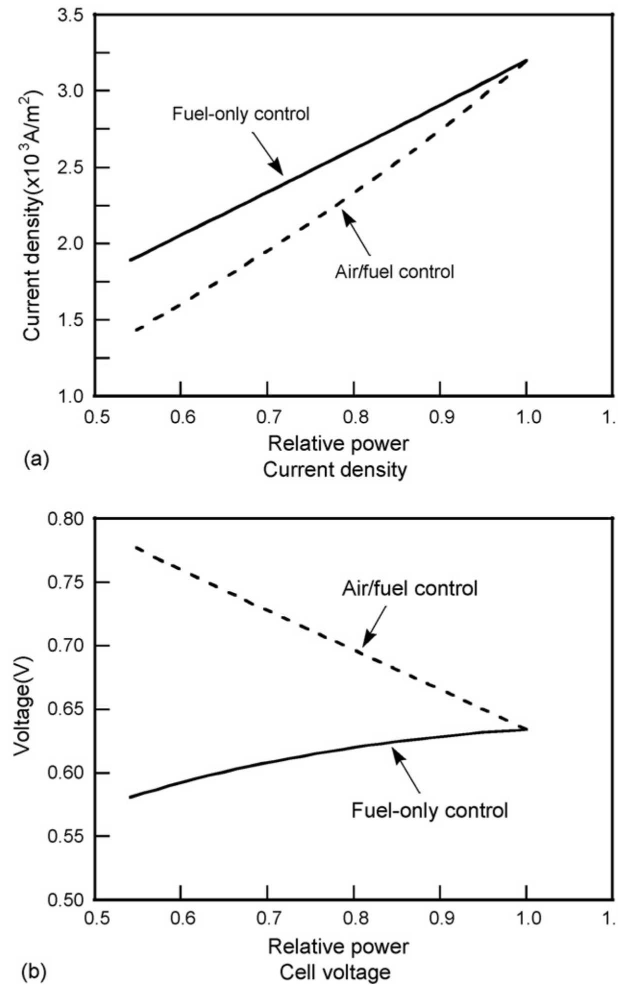

Fig. 10. Performance characteristics of the SOFC-only system at part-load conditions.

cell temperature of the fuel-only control mode in Fig. 9(b) is related to the increased excessive air due to constant air supply. Fig. 10(a) shows that the current density of the air/fuel control mode is lower than that of the other case. This is only influenced by the fuel supplied into the anode chamber because the fuel utilization factor is kept constant during part-load operation. The cell voltage in the air/fuel control mode increases due to the influences of both the high cell temperature and low current density as the SOFC power decreases (Fig. 10(b)). As a result, it is shown in Fig. 11 that the SOFC efficiency in the air/fuel control mode at part-load conditions is higher than that in the fuel-only control mode. The increased thermal efficiency of the air/fuel control mode is caused by the increase in cell voltage. The supplied air in a SOFC power system cannot be manipulated because the air-supply unit is not included in this system. The influence of the air-supply methods can be investigated in the SOFC/GT hybrid system.

4.3. Performance characteristics of the SOFC/GT hybrid system

Fig. 12 shows the operational concepts of three different part-load control modes of the SOFC/GT hybrid system. For the air/fuel control cases, *i.e.*, the rotational speed and VIGV control modes, when the air supply is reduced in either the rotational speed or VIGV control modes at part-load operating conditions, the supplied fuel is simultaneously reduced to maintain the same turbine inlet temperature as that at the full power condition. On

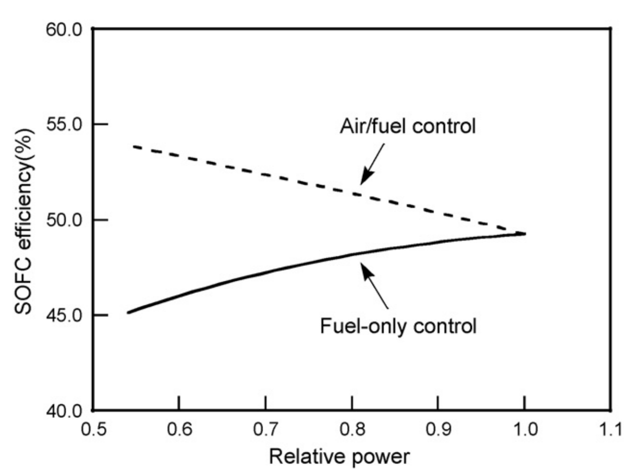

Fig. 11. Thermal efficiency of the SOFC-only system at part-load operating conditions.

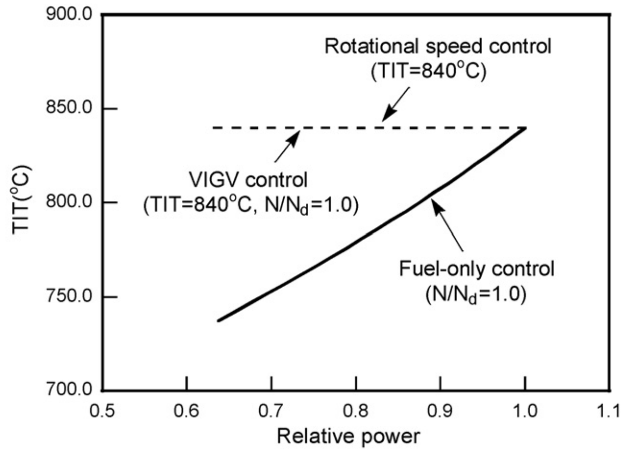

Fig. 12. Turbine inlet temperature of the SOFC/GT hybrid system at part-load operating conditions.

the other hand, in the case of the fuel-only control mode, due to the reduction in the supplied fuel without air supply control, the turbine inlet temperature decreases during part-load conditions.

As shown in Fig. 13, different control modes change the amount of power produced by the gas turbine and the SOFC. In the case of the fuel-only control mode, the reduction in power produced by the gas turbine at part-load conditions is smaller than that of the other two cases because of the small change in the supplied air. The reason why the rotational speed control mode produces more gas turbine power than the VIGV control case is closely related to the change in the isentropic efficiency of the compressor, which dominantly influences the gas turbine performance as described earlier. With a required power level at part-load operating conditions, the difference between the required power and produced power of the gas turbine is the power produced by the SOFC. Fig. 14 shows the patterns of the power split ratio, defined as the ratio of the gas turbine power to the SOFC power, at part-load conditions. In the fuel-only control mode, the power split ratio increases as the total produced power is reduced because the SOFC power is reduced more rapidly than the gas turbine power during part-load operation. In the cases of air/fuel control modes, the power split ratio decreases with the reduced total power and, therefore, the influence of the gas turbine performance on the hybrid system becomes less dominant than that in the fuel-only control mode.

Fig. 15 shows the change in the thermal efficiency of the SOFC/GT hybrid system at part-load operating ranges. The gas turbine enhances the thermal efficiency about 5–10% for all operating conditions. The worst efficiency of the fuel-only control mode is closely related to the decreased cell temperature of the SOFC and, as a consequence, the low turbine inlet temperature of the gas turbine. It is also significantly related to the relatively high power split ratio as described above. The air/fuel control modes do not significantly influence the SOFC efficiency. However, they have a strong influence on the performance of the SOFC/GT hybrid system as a whole. This means that the part-load efficiency of the SOFC/GT hybrid system is influenced by the change in the performance characteristics of the gas turbine. The part-load efficiency of the VIGV control mode is much higher than that of the fuel-only control mode. This result shows that the VIGV control mode can be an alternative to the variable speed control mode, especially when the MW-class SOFC/GT hybrid system, which requires a large-

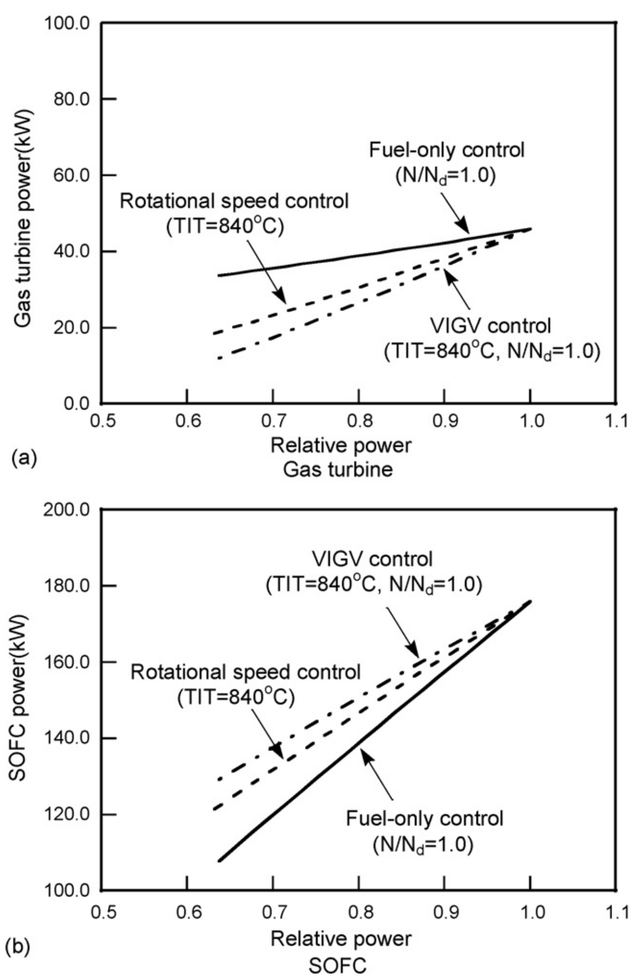

Fig. 13. Power generated from gas turbine and SOFC in the SOFC/GT hybrid system.

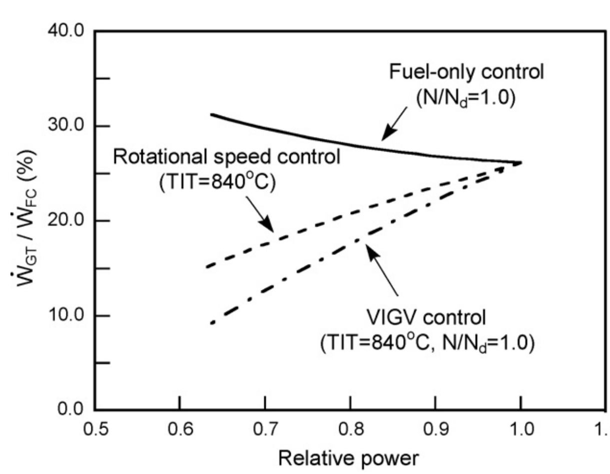

Fig. 14. Power split ratio of the SOFC/GT hybrid system.

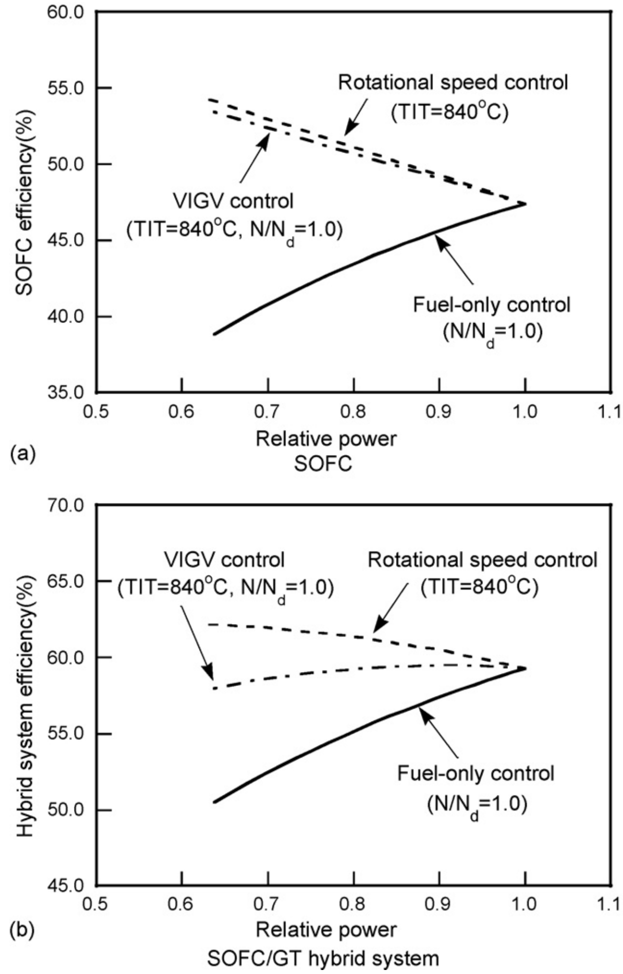

Fig. 15. Thermal efficiency at part-load operating conditions of the SOFC/GT hybrid system.

scale gas turbine operating at a constant speed during part-load operation, is considered.

5. Conclusions

Based on the results of the performance analysis of the SOFC/GT hybrid system under part-load operating conditions with three different control modes, some important conclusions are reached as follows.

Although the power generated by a gas turbine is much smaller than that generated by a SOFC, the gas turbine plays an important role in the part-load operations of a SOFC/GT hybrid system. Therefore, it is necessary to choose the appropriate control mode to improve part-load efficiency. For this purpose, it is important to maintain the cell temperature and turbine inlet temperature as high as possible. For this purpose, the simultaneous controls of both the supplied fuel and air are required for part-load operation at high efficiency. The air/fuel control modes also reduce the relative amount of power generated by the gas turbine under part-load operating conditions. Of these modes, the rotational speed control mode provides better performance than the VIGV control mode. The performance difference between the two air/fuel control modes is closely related to the pattern of the compressor isentropic efficiency of the gas turbine.

Although the VIGV control mode produces worse part-load system efficiency than the rotational speed control mode, it can be a good candidate for use in MW-class SOFC/GT hybrid systems where the rotational speed control cannot be used.

Acknowledgement

This work was supported by the BK21 Project in 2006.

References

[1] R.A. George, Status of tubular SOFC field unit demonstrations, J. Power Sources 86 (2000) 134–139.
[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, J. Eng. Gas Turbines Power-Trans. ASME 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] S.E. Veyo, W.L. Lundberg, S.D. Vora, K.P. Litzinger, Tubular SOFC hybrid power system status, ASME Paper GT2003-38943, 2003.
[5] D. Tucker, L. Lawson, R. Gemmen, R. Dennis, Evaluation of hybrid fuel cell turbine system startup with compressor bleed, ASME Paper GT2005-68784, 2005.
[6] D. Tucker, L. Lawson, J. VanOsdol, J. Kislear, A. Akinbobuyi, Examination of ambient pressure effects on hybrid solid oxide fuel cell turbine system operation using hardware simulation, ASME Paper GT2006-91291, 2006.
[7] R.A. Roberts, J. Brouwer, E. Liese, R.S. Gemmen, Development of controls for dynamic operation of carbonate fuel cell/gas turbine hybrid systems, ASME Paper GT2005-68774, 2005.
[8] R.A. Roberts, J. Brouwer, G.S. Samuelsen, Fuel cell/gas turbine hybrid system control for daily load profile and ambient condition variation, ASME Paper GT2006-90741, 2006.
[9] G.D. Agnew, J. Townsend, R.R. Moriz, M. Bozzolo, S. Berenyi, R. Duge, Progress in the development of a low cost 1MW SOFC hybrid, ASME Paper GT2004-53350, 2004.
[10] G.D. Agnew, M. Bozzolo, R.R. Moritz, S. Berenyi, The design and integration of the Rolls–Royce fuel cell systems 1MW SOFC, ASME Paper GT2005-69122, 2005.
[11] H. Ghezel-Ayagh, J. Walzak, D. Patel, J. Daly, H. Maru, R. Sanderson, W. Livingood, State of direct fuel cell/turbine systems development, J. Power Sources 152 (2005) 219–225.
[12] H. Ghezel-Ayagh, R. Sanderson, J. Walzak, Development of hybrid power systems based on direct fuel cell/turbine cycle, ASME Paper GT2005-69119, 2005.
[13] 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, J. Eng. Gas Turbines Power-Trans. ASME 125 (2003) 51–58.
[14] S. Campanari, Full-load and part-load performance prediction for integrated SOFC and micro turbine systems, J. Eng. Gas Turbines Power-Trans. ASME 122 (2000) 239–246.
[15] P. Costamagna, L. Magistri, A.F. Massardo, Design and part-load performance of a hybrid system based on a solid oxide fuel cell reactor and micro gas turbine, J. Power Sources 96 (2001) 352–368.
[16] T.W. Song, J.L. Sohn, T.S. Kim, S.T. Ro, Performance characteristics of a MW-class SOFC/GT hybrid system based on a commercially available gas turbine, J. Power Sources 158 (2006) 361–367.

[17] T.W. Song, J.L. Sohn, J.H. Kim, T.S. Kim, S.T. Ro, K. Suzuki, Performance analysis of a solid oxide fuel cell/micro gas turbine based on a quasi-two dimensional model, J. Power Sources 142 (2005) 30–42.
[18] H.I.H. Saravanamuttoo, G.F.C. Rogers, H. Cohen, Gas Turbine Theory, 5th ed., Prentice Hall, 2001.
[19] N. Zhang, R. Cai, Analytical solutions and typical characteristics of part-load performances of single shaft gas turbine and its cogeneration, Ener. Conv. Manage. 43 (2002) 1323–1337.
[20] J.H. Kim, Analysis on transient behavior of gas turbines for power generation, PhD dissertation, Seoul National University, 2000.