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Design performance analysis of pressurized solid oxide fuel cell/gas turbine hybrid systems considering temperature constraints

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Abstract

This study presents critical aspects and their influence on the performance of hybrid power systems combining a pressurized solid oxide fuel cell (SOFC) and a gas turbine (GT). Two types of hybrid system configurations with internal and external reforming have been analyzed. In order to examine the effect of matching between the fuel cell temperature and the turbine inlet temperature on the hybrid system performance, we considered air bypass after the compressor as well as additional fuel supply to the turbine side. This study focuses on the limitation of the temperature difference at the fuel cell stack and its influence on the performances of the two hybrid systems. Performances of the hybrid systems are also compared with those of simple SOFC systems, and the extent of performance enhancement is evaluated. The system with internal reforming gives better efficiency and power capacity for all design conditions than the system with external reforming under the same constraints. Its efficiency gain over the SOFC only system is considerable, while that of the system with external reforming is far less. As the temperature difference at the cell becomes smaller, the system performance generally degrades. The system with internal reforming is less influenced by the constraint of the cell temperature difference.

Keywords: Solid oxide fuel cell; Gas turbine; Hybrid system; Fuel cell temperature; Turbine inlet temperature; Temperature difference

1. Introduction

The fuel cell is expected to be one of the most promising power sources for the future in various applications because of its high efficiency and ultra low emission of environmentally harmful gases. Among others, high temperature fuel cells such as the solid oxide fuel cell (SOFC) and the molten carbonate fuel cell (MCFC) are considered extremely suitable for electric power plant application. In particular, the solid oxide fuel cell is the most promising because its high cell temperature allows not only high fuel cell efficiency but also the additional possibility of its acting as a high temperature heat source for various purposes [1]. The most beneficial way of utilizing this potential is to smoothly combine the SOFC with the gas turbine (GT), which also operates at high temperature. Moreover, the wide range of the cell's operating temperature (600–1000 °C) allows more design flexibility of the hybrid system than other fuel cells do. Accordingly, the hybrid system has been receiving increasing attention, and R&D efforts have been initiated worldwide. These efforts have resulted in the realization of a 220 kW SOFC/GT hybrid system based on a proven tubular SOFC and a commercial micro gas turbine [2,3]. As well as the tubular type cell stacks, planar SOFC stacks are also being developed for the hybrid system [4,5]. Most of the currently developed systems are still small compared with other conventional power plants because the SOFC technology has not fully matured yet. Thus, these current systems are primarily considered for applications in distributed generation [6].

The initial theoretical works on the combination of high temperature fuel cells and gas turbine extends into the early and mid 1990's [7]. Since then, many researchers have demonstrated thermodynamic advantages and accompanying challenges of

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Nomenclature

A	hybrid system with internal reforming
AR	air bypass ratio
B	hybrid system with external reforming
F	Faraday constant (96,486 C mol^{-1})
FCT	fuel cell temperature (°C)
FR	additional fuel supply ratio
GT	gas turbine
h	specific enthalpy (kJ kg^{-1})
$\bar{h}$	molar specific enthalpy (kJ kmol^{-1})
I	current (A)
LHV	lower heating value (kJ kg^{-1} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{n}$	molar flow rate (kmol s^{-1})
P	pressure (bar)
$\dot{Q}$	heat transfer rate (kW)
SCR	steam carbon ratio
SOFC	solid oxide fuel cell
T	temperature (°C)
ΔT_{cell}	temperature difference at the fuel cell (°C)
TIT	turbine inlet temperature (°C)
U	fuel utilization factor
V	voltage (V)
$\dot{W}$	power (kW)

Greek letter

η	efficiency, effectiveness

Subscript

a	air
AC	alternating current
aux	auxiliary
C	compressor
comb	combustor
conv	conversion
DC	direct current
f	fuel
FC	fuel cell
FS	fuel cell only system
gen	generator
GT	gas turbine
HS	hybrid system
i	composition
in	inlet
m	mechanical
n	nominal condition
out	outlet
s	isentropic
rec	recuperator
ref	reformer
T	turbine

various system configurations. First, several design options are available for combining the fuel cell and the gas turbine such as the selection of the operating pressure of the fuel cell (pressurized versus ambient pressure) [8]. Another design option is to determine the reforming method for generating hydrogen from the conventional fuel (natural gas). The most common reforming method adopted for the SOFC is steam reforming and there are also diverse methods of supplying heat to the endothermic reforming reaction. Fuel cell and hybrid system performances depend greatly on the reforming method [9]. Due to high flexibility in the design of the hybrid system, diverse studies have been performed on the SOFC/GT hybrid systems including parametric analysis of design variables [10], study of optimized matching between gas turbine and the SOFC [11], studies of the effects of system configuration, design parameters and technology levels [12], and effect of adopting advanced gas turbine cycles [13] on the system performance. In addition, the combination of the gas turbine with multi-stage and networked SOFC stacks [14,15] has also been proposed.

The successful development of a highly efficient hybrid system must overcome many practical problems because the SOFC technology is not as reliable as other proven technologies. In addition, SOFC usually requires relatively complicated auxiliary systems including the fuel processing system (mainly the reforming process). Another significant item to consider is the matching of design parameters between the SOFC and the gas turbine. Sometimes, a thermodynamically optimal system design cannot be achieved because components cannot be matched easily. All these factors may also limit the obtainable performance of the SOFC/GT hybrid system.

Therefore, a critical analysis on the practical problems in the combination of two sub-systems is very important. Moreover, a study is required on the subject of various ways of matching major temperature parameters and their influences on the performance of different hybrid system configurations. In this regard, this study investigates effects of different methods of matching temperature parameters and the restrictions of the temperatures on the design performance of the pressurized SOFC/GT hybrid system. Two different system layouts adopting internal and external reforming systems are analyzed. Unlike the conventional thermal systems, the hybrid system requires two main temperatures representing the system (turbine inlet temperature and fuel cell temperature) because it consists of two absolutely different sub-systems. Therefore, the overall system performance is examined in terms of the interrelationship between the two temperatures. In addition, the limitation of the temperature difference at the fuel cell stack and its influence on the design performances of the two hybrid systems are investigated. Performances of the hybrid systems are also compared with those of simple SOFC systems, and the extent of performance enhancement is evaluated.

2. Hybrid system configurations

Two design configurations, with the major difference being the fuel reforming method, are considered as shown in Fig. 1.

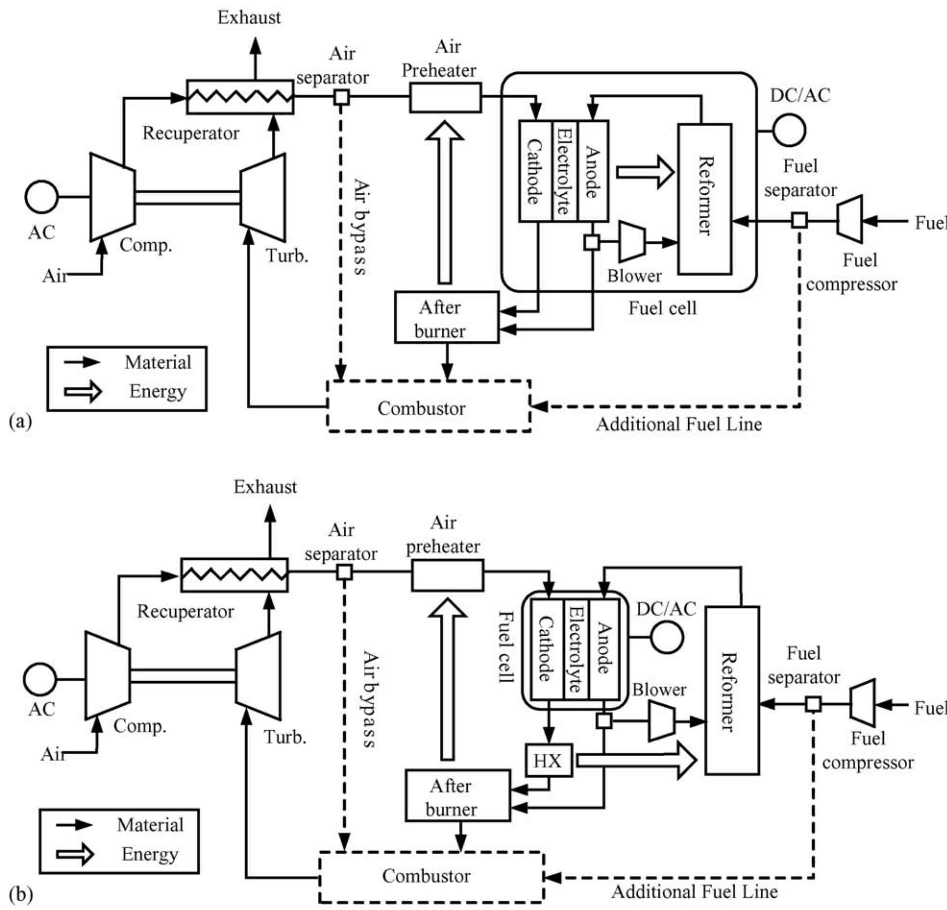

Fig. 1. Pressurized SOFC/GT hybrid systems: (a) configuration A—internal reforming and (b) configuration B—external reforming.

Both of them are pressurized systems in terms of the operating pressures of their fuel cells, but adopt different reforming methods. Air flows into the compressor and is heated at the recuperator. The air coming from the recuperator is further heated at the preheater before it flows into the cathode of the fuel cell. The heat required for the air preheater is transferred from the after burner. The important role of the recuperator and the air preheater is to heat the air up to the minimum cell inlet temperature required. Fuel and air react at the fuel cell to generate DC power, after which the gas expands at the turbine to generate additional power. Specific features of each configuration are as follows.

2.1. Configuration A

This system adopts the internal reformer, in which steam reforming takes place. Recirculation of the anode exit gas, containing sufficient amount of steam, supplies the reforming steam. The reformer is in thermal contact with the fuel cell, which supplies the reforming heat. This concept of the reforming process is basically similar to the one under commercial development [2,3]. However, the recirculation is modeled to be performed by a blower instead of an ejector of the references. No specific geometric information for the reformer is used because this study aims at only the thermodynamic analysis.

2.2. Configuration B

This system is different from the previous one in that it adopts the external reformer. The recirculation of anode exit gas is also adopted for supplying reforming steam. Various methods can be used to provide heat to the external reformer [9,16]. Here, the reforming heat is transferred from the cathode exit gas, which is at a sufficiently high temperature. This method provides higher performance than other external reforming schemes [16]. A similar reforming heat exchange concept is available in a system under development [17].

2.3. Matching of SOFC and GT with a constraint

The dotted lines shown in both configurations represent additional fuel supply and air bypass, respectively. The purpose of these two options is to arbitrarily assign the turbine inlet temperature (TIT) at a given fuel cell operating temperature (FCT). These additional functions are required to combine two independently designed sub-systems (SOFC and GT). By modulating the amounts of additional fuel supply and air bypass, various combinations of the two main temperatures can be covered and their effect on the hybrid system performance can be investigated.

Another important design parameter is the temperature difference (rise) at the fuel cell stack. In a high temperature fuel cell, the extreme temperature gradient in the cell stack causes severe thermal stress of the cell material. The situation may be extremely severe in case of the SOFC made of very brittle ceramic material. Thermal stress analysis is possible only after detailed temperature distribution inside the cell is known. This is beyond the scope of this study because the cell is modeled as a lumped control volume as will be explained in Section 3. However, it is quite reasonable to assume that a larger difference between the average cell operating temperature and the cell inlet air temperature may cause a greater temperature gradient and results in a greater thermal stress. Therefore, the temperature difference at the cell is an important limiting factor in the preliminary design stage and should be considered in practical performance analysis. Accordingly, this study deals with the effects of the cell temperature difference on the system performance.

In summary, three design conditions (turbine inlet temperature, fuel cell temperature and temperature difference at the cell) should be satisfied simultaneously by using air bypass or additional fuel supply, and by modulating the degree of air preheating in front of the cell. The main purposes of the air bypass and the additional fuel supply are to limit and increase the TIT, respectively. The heat supply to the air preheater in front of the cell is regulated to meet the assigned cell inlet temperature (i.e. temperature rise at the cell). If the air temperature at the recuperator exit is sufficiently high, air needs not be preheated and moreover the heat recovery at the recuperator is limited. Since this study deals with the design performance, all cases are considered to be independent design cases.

3. Analysis

Each component is modeled as a lumped control volume. The fuel is methane, which needs to be converted into hydrogen at the reformer. The steam reforming process is considered as follows:

$$\text{Fuel reforming}: \quad CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{1}$$

$$\text{Steam shifting}: \quad CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2}$$

Theoretically, 1 mol of methane produces 4 mol of hydrogen for a complete reaction. However, the degree of reaction depends on the reaction environment (temperature and pressure). Thus, the reactions are considered to occur at equilibrium conditions. Therefore, the fuel to the anode includes carbon monoxide and remaining methane, even though hydrogen is the major component. The steam carbon ratio defined as follows determines the amount of steam supplied to the reformer:

$$\text{SCR} = \frac{\dot{n}_{H_2O}}{\dot{n}_{CH_4}} \tag{3}$$

The fuel utilization factor at the cell is defined as the ratio between reacted to supplied effective fuel components at the cell as follows:

$$U = \frac{(\dot{n}_{H_2} + \dot{n}_{CO})_{\text{reacted}}}{(\dot{n}_{H_2} + \dot{n}_{CO})_{\text{supplied}}} \tag{4}$$

Both hydrogen and carbon monoxide generated by the steam reforming process participate in the electrochemical reactions:

$$\text{Hydrogen}: \quad H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{5}$$

$$\text{Carbon monoxide}: \quad CO + \tfrac{1}{2}O_2 \rightarrow CO_2 \tag{6}$$

The DC power generated at the fuel cell is calculated as follows:

$$\dot{W}_{\text{FC,DC}} = VI = V(\dot{n}_{H_2} + \dot{n}_{CO})_{\text{reacted}}\, 2F \tag{7}$$

The final AC power from the SOFC is calculated as follows, considering the DC to AC conversion loss:

$$\dot{W}_{\text{FC,AC}} = \dot{W}_{\text{FC,DC}}\, \eta_{\text{conv}} \tag{8}$$

In the fuel cell with an internal reformer (configuration A), heat is transferred from the cell to the reformer to maintain the endothermic steam reforming reaction. On the other hand, in the system with an external reformer (configuration B), the cell operates at adiabatic condition and the required heat for the reforming process must be supplied from an external source. Thus, the energy balances at the cell and the reformer are presented by the following equations:

$$\text{Cell}: \quad \sum_{\text{in}} \dot{n}_i \bar{h}_i + \dot{Q}_{\text{cell}} = \sum_{\text{out}} \dot{n}_i \bar{h}_i + \dot{W}_{\text{FC,DC}} \tag{9}$$

where $\dot{Q}_{\text{cell}} = 0$ for a system with an external reformer; $\dot{Q}_{\text{cell}} < 0$ for a system with an internal reformer:

$$\text{Reformer}: \quad \sum_{\text{in}} \dot{n}_i \bar{h}_i + \dot{Q}_{\text{ref}} = \sum_{\text{out}} \dot{n}_i \bar{h}_i \tag{10}$$

where $\dot{Q}_{\text{ref}} = -\dot{Q}_{\text{cell}}$ for an internal reformer.

The cell voltage depends on the cell material, cell structure (geometry), and operating pressure and temperature of the fuel cell. Therefore, the cell voltage can be assigned in detail only when cell design specifications are given. In this work, a reasonable reference value (0.7 V) is given for a nominal design condition (cell temperature of 800 °C and pressure of 3.5 bar), and its variation due to the cell operating temperature and pressure is assumed on the basis of published correlations. Since this study deals with design analysis (not an operating analysis based on a given fuel cell), the current density is assumed to be constant for all cases. Accordingly, difference in the design cell power, which will be presented in Section 4, requires different cell size. Given the nominal value, a published correlation [18] is used to simulate the dependence of the cell voltage on the temperature. The voltage increases as the operating temperature increases. The cell voltage also intensifies as the operating pressure increases. This effect is modeled by using a published pressure dependent correlation [19]. Consequently, the cell voltage can be predicted as a function of cell temperature and pressure:

$$V = V_n\, f(T_{\text{cell}}, P_{\text{cell}}) \tag{11}$$

Any combustible compositions (hydrogen, carbon monoxide, methane) from the anode are burned at the after burner. Some portion of the heat is transferred to the air preheater to meet the required cell inlet air temperature. The energy balance at the after burner considering the heat transfer to the preheater is as follows:

$$\sum_{\text{in}} \dot{n}_i \bar{h}_i + \dot{Q} = \sum_{\text{out}} \dot{n}_i \bar{h}_i, \quad \text{where } \dot{Q} < 0 \tag{12}$$

The resultant exit gas determines the turbine inlet temperature. The energy balance at the main combustor is similar to Eq. (12) without the external heat transfer. The compressor and turbine efficiencies and recuperator effectiveness are defined as follows:

$$\eta_C = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}} \tag{13}$$

$$\eta_T = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{14}$$

$$\eta_{rec} = \frac{T_{cold,out} - T_{cold,in}}{T_{hot,in} - T_{cold,in}} \tag{15}$$

The gas turbine power is calculated as follows:

$$\dot{W}_{GT,AC} = (\dot{W}_T\, \eta_m - \dot{W}_C)\eta_{gen} - \dot{W}_{aux} \tag{16}$$

The power ratio is defined as follows:

$$\text{Power ratio} = \frac{\dot{W}_{FC,AC}}{\dot{W}_{GT,AC}} \tag{17}$$

The total hybrid system power and the system efficiency are defined as follows:

$$\dot{W}_{HS} = \dot{W}_{FC,AC} + \dot{W}_{GT,AC} \tag{18}$$

$$\eta_{HS} = \frac{\dot{W}_{HS}}{(\dot{m}\,\text{LHV})_f} \tag{19}$$

The temperature difference at the cell is defined as follows:

$$\Delta T_{cell} = \text{FCT} - \text{cathode inlet temperature} \tag{20}$$

As explained in Section 2, in order to meet FCT and TIT simultaneously, fuel should be directly supplied or air should be bypassed to the combustor. These additional functions are represented by the two parameters (fuel supply ratio and air bypass ratio) as follows:

$$\text{FR} = \frac{\dot{m}_{f,comb}}{\dot{m}_{f,total}} \tag{21}$$

$$\text{AR} = \frac{\dot{m}_{a,bypass}}{\dot{m}_{a,in}} \tag{22}$$

Assumed component parameters are listed in Table 1. The compressor pressure ratio is set 3.5 to simulate the design status of current micro gas turbines. This study is not confined to certain specifications of components such as the absolute magnitude (power) of the SOFC. On the contrary, the relative powers of the two components are important. Therefore, the air flow rate can be chosen arbitrarily. For the sake of convenience, a constant air supply rate at the entire system inlet (compressor inlet) is set to 1.0 kg s^{-1} in all cases. If the turbine exhaust temperature is high enough to raise the air temperature sufficiently, the air preheater is not required and heat addition at the recuperator needs to be reduced (low recuperator effectiveness) to meet the cell inlet temperature. This usually happens when TIT is sufficiently higher than FCT. A process analysis software [20] is used for the simulation.

Table 1
Component parameters used for the analysis

Ambient temperature (°C)	15
Ambient pressure (kPa)	101.3
Steam carbon ratio	3
Utilization factor	0.7
Reference cell voltage (V)	0.7
Compressor pressure ratio	3.5
Compressor efficiency (%)	78
Turbine efficiency (%)	85
Reference recuperator effectiveness	0.83
DC to AC conversion efficiency (%)	93
Mechanical efficiency (%)	96
Generator efficiency (%)	93
Compressor inlet air flow rate (kg s^{-1})	1.0

4. Results and discussion

Both the internally and externally reformed systems were analyzed by considering the temperature difference at the fuel cell as the main design constraint. Different performance behaviors have been examined for these systems, shown in Fig. 1. In order to investigate the effect of the severity of the fuel cell constraint on the system performance, two different ΔT_{cell} values of 100 and 200 °C are assumed. The design range of the operating temperature of the fuel cell is given from 700 to 1000 °C. The range of the turbine inlet temperature is set from 750 to 1150 °C by considering design practice of micro and small gas turbines.

Even though the power distribution between the SOFC and the gas turbine varies among different system configurations, it is generally accepted that the power portion of the SOFC is greater than that of the gas turbine. Thus, the performance of SOFC only system is first studied as a guideline, prior to the examination of the hybrid systems. This preliminary evaluation provides insights into the different fundamental characteristics of the two reforming methods and the effect of the cell temperature constraint on the fuel cell performance. Based on this preliminary study, performance enhancement due to hybridization can also be estimated. Both the internally and externally reformed systems of Fig. 1 are considered after removing the gas turbine components. Of course, the SOFC operates at nearly ambient pressure in this fuel cell only system. For a wide fuel cell temperature range, performance is analyzed with a constraint on the cell temperature difference. The SOFC only systems do not require air bypass and additional fuel supply. The recuperator is not needed either because the air can be heated sufficiently by the preheater up to the required cathode inlet temperature.

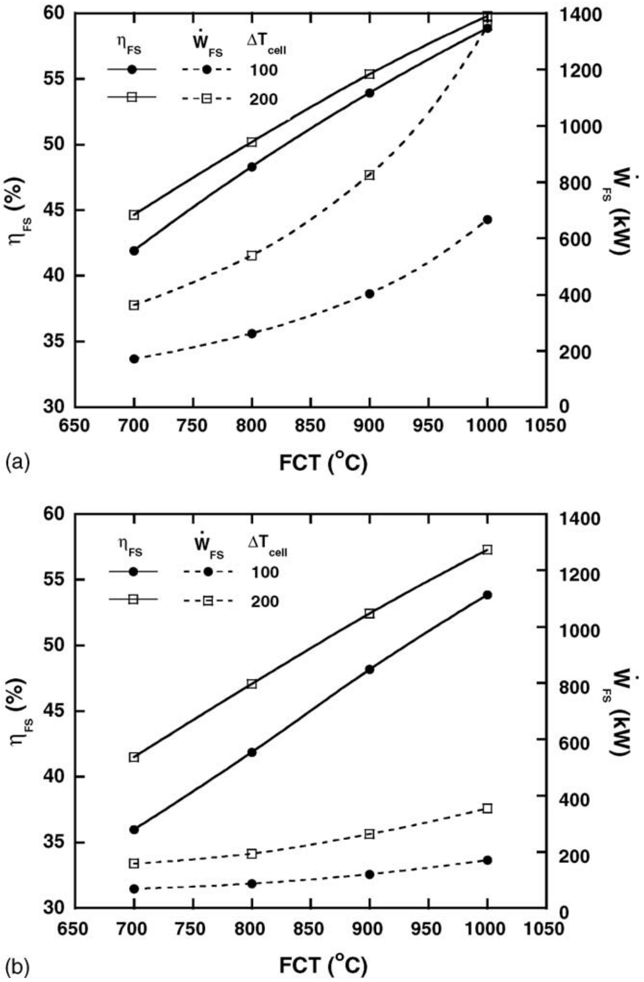

Fig. 2. Performance of SOFC only systems: (a) internal reforming and (b) external reforming.

Results are shown in Fig. 2. The internal reforming gives better performance than the external reforming. In particular, given the same cell temperature difference, the power capability of the internally reformed system is greater than that of the externally reformed system. Since the reformer acts as a heat sink in the internally reformed cell stack, cooling air flow per unit fuel flow required to maintain the same cell temperature is less than that of the externally reformed SOFC. Thus, since air flow rate is fixed in this study, more fuel reacts in the internally reformed SOFC, leading to greater power. A greater temperature difference (200 °C against 100 °C) at the cell requires a larger fuel to air ratio, and thus, enables larger power for a given air flow rate. At a fixed cell temperature, the cell stack efficiencies of all cases should the same because the cell voltage is the same. However, the system efficiencies are slightly different as clearly shown in the figure because relative size of the auxiliary power consumption such as air compressor power is different. For example, the externally reformed system produces less cell power, but its auxiliary power consumption is comparable to that of the internally reformed system because the air flow rate is the same. Therefore, the relative portion of the auxiliary power consumption is greater in the externally reformed system compared with the internally reformed system. Thus, the system efficiency of the externally reformed system is lower than that of the internally reformed system. A similar reasoning is applied to the explanation of the effect of the temperature difference at the cell on the system efficiency. The smaller cell temperature difference produces smaller cell power for the same air flow rate, resulting in a relatively larger portion of the auxiliary power consumption and thus a lower system efficiency. The system efficiency of the internally reformed SOFC is higher than the externally reformed SOFC by 3–5 percent points, depending on the cell temperature and ΔT_{cell}. The efficiency gap between the two systems becomes larger as the cell temperature difference becomes smaller.

From now on, the results of the hybrid systems will be discussed. Design parameters and performance of the system with internal reforming (configuration A) are presented first. Figs. 3 and 4 show the additional fuel supply ratio and the air

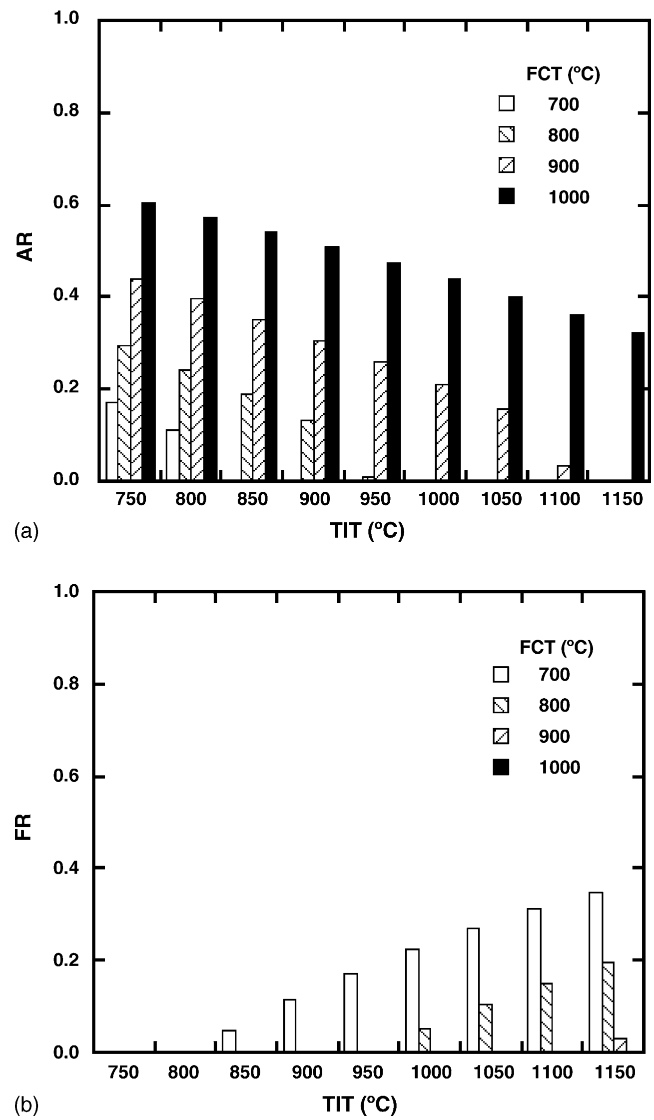

Fig. 3. Air bypass ratio and additional fuel supply ratio of configuration A with ΔT_{cell} of 200 °C: (a) air bypass ratio and (b) additional fuel supply ratio.

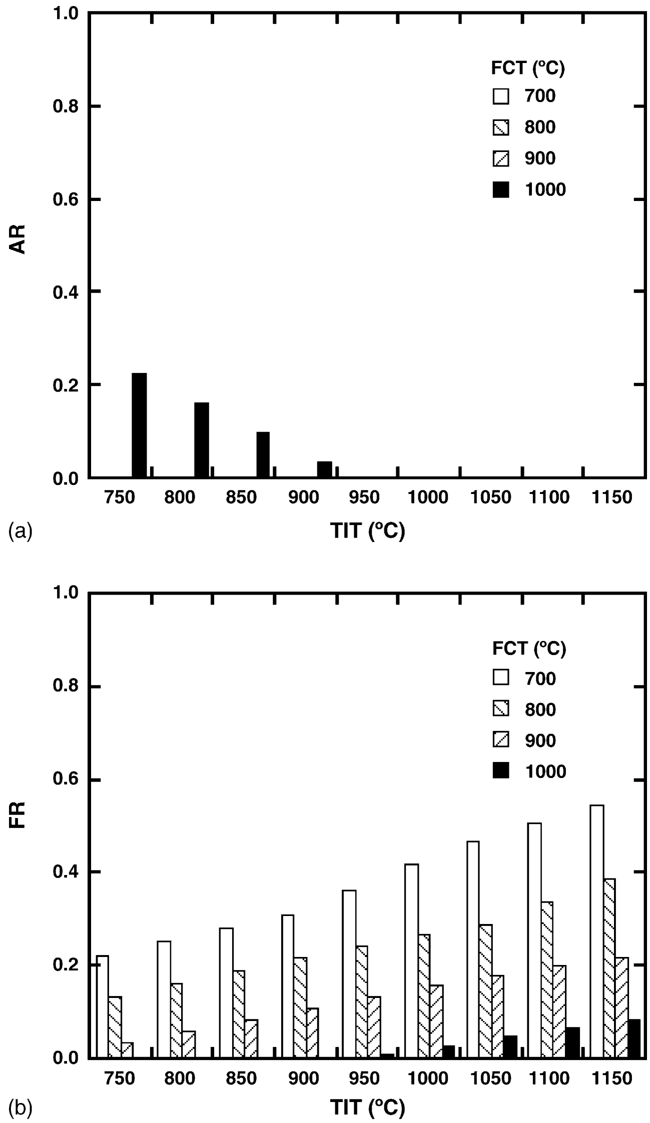

Fig. 4. Air bypass ratio and additional fuel supply ratio of configuration A with ΔT_{cell} of 100 °C: (a) air bypass ratio and (b) additional fuel supply ratio.

bypass ratio, defined by Eqs. (21) and (22), respectively, for two ΔT_{cell} values. Let us first examine the relaxed constraint (ΔT_{cell} of 200 °C) in Fig. 3. For a fixed FCT, if the required turbine inlet temperature is sufficiently low, a part of the compressed air is bypassed to the combustor in order to satisfy the low turbine inlet temperature. As TIT increases, the ratio of bypassed air should be reduced. Finally, at a certain TIT value, air does not need to be bypassed. For example, this TIT occurs between 950 and 1000 °C for FCT of 800 °C. Beyond this TIT, fuel should be additionally supplied to the combustor. Further increase of the TIT requires increase of the additional fuel supply. As the FCT becomes higher, either the air bypass ratio should be increased for low TITs or the additional fuel supply should be reduced for high TITs. In case of a smaller ΔT_{cell} (100 °C) of Fig. 4, almost all TIT conditions require additional fuel supply except for the cases where FCT is sufficiently high and TIT is relatively low. As explained in the results of the SOFC only systems, a design with smaller ΔT_{cell} leads to a smaller fuel supply at the cell. Therefore, the amount of combustible component present at the exit of the fuel cell also decreases and this tends to reduce the turbine inlet temperature. Then, in order to meet an equivalent TIT, more fuel should be supplied to the combustor. As TIT increases, turbine exhaust temperature, and thus the air temperature at the recuperator outlet also increases. At a certain TIT, the air preheater becomes unnecessary because the recuperator outlet temperature is high enough to meet the designated cathode inlet temperature. If TIT increases further, the required recuperator effectiveness is smaller than the reference value. Fig. 5 illustrates the resulting recuperator effectiveness.

The performance parameters of configuration A with ΔT_{cell} of 200 °C are shown in Fig. 6. Variations of the SOFC power with TIT can be explained in terms of the air bypass ratio. If the air flow rate to the cathode were constant without the bypass, SOFC power would not change effectively because cell voltage and fuel to air ratio at the cell would remain almost constant. This

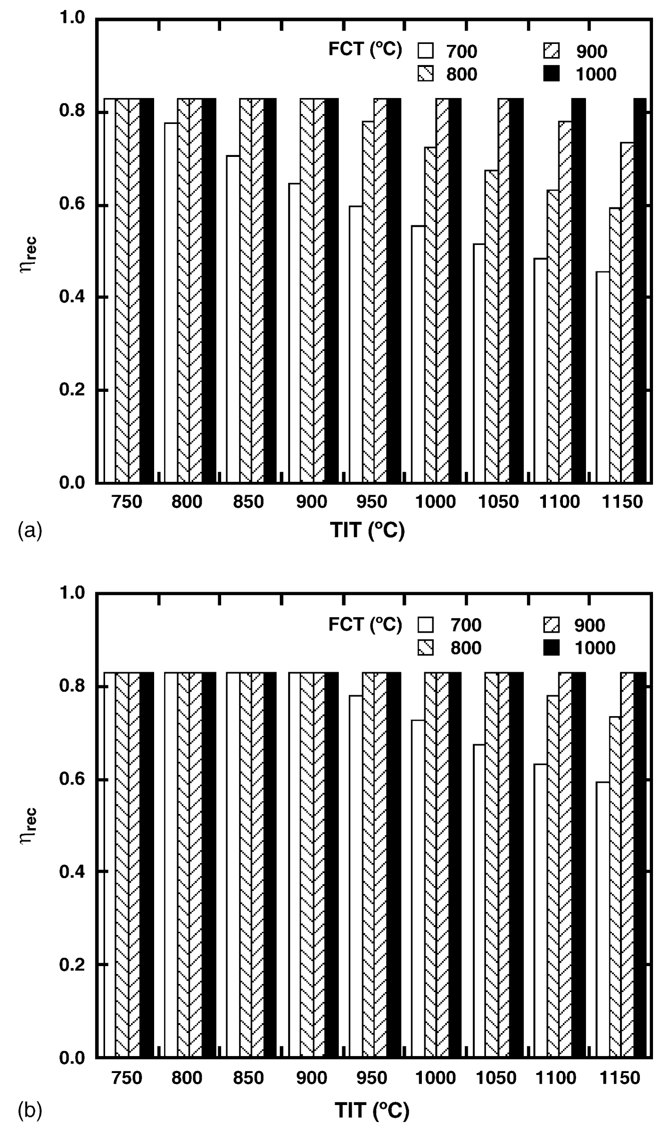

Fig. 5. Recuperator effectiveness of configuration A: (a) ΔT_{cell} of 200 °C and (b) ΔT_{cell} of 100 °C.

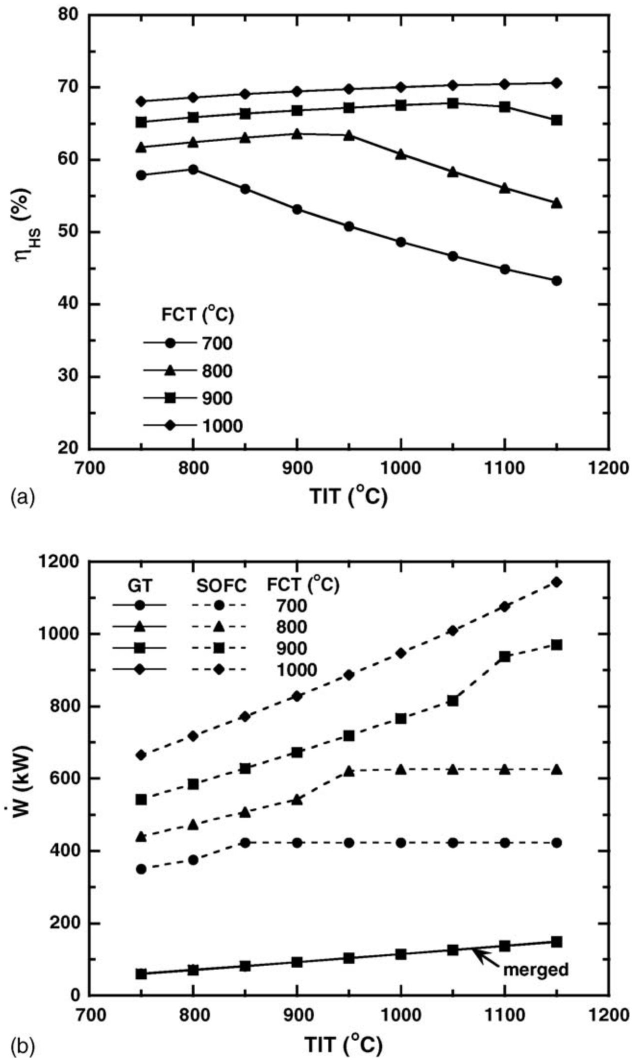

Fig. 6. Performance of configuration A with ΔT_{cell} of 200 °C: (a) system efficiency and (b) SOFC and GT power.

is true for design conditions with sufficiently low FCT values. For example, in case of FCT of 700 °C, the SOFC power remains nearly constant except for the low TIT range (less than 850 °C) where air needs to be bypassed. For high FCT values such as 900 and 1000 °C, the SOFC power decreases with decreasing TIT because of the increasing air bypass ratio. For a fixed FCT, higher TIT contributes to the increase of the hybrid system power due to increased GT power. Moreover, since FCT has little effect on GT power, the GT power curves for different FCTs almost merge into a single curve. For all conditions, the SOFC power is far greater than the GT power. For a fixed FCT, the power ratio, defined by Eq. (17), becomes higher with decreasing TIT. It ranges from 3.5 to 11 in the design conditions covered in the figure.

For a fixed FCT condition, the system efficiency increases until a certain TIT value, after which it decreases. Therefore, an optimal TIT for a fixed FCT exists. The optimal TIT value increases as FCT increases. For the highest FCT (1000 °C), the optimal point lies beyond the TIT limit considered. Comparison of Figs. 6 and 3 reveals that the optimal points nearly correspond to the points of conversion from air bypass to additional fuel supply. To the left (low TIT) of these points, efficiency is a very weak function of TIT. This indicates that the air bypass considerably influences the system power but it does not affect the system efficiency considerably. However, to the right (high TIT), efficiency decreases rather rapidly with increasing TIT. This implies that the additional fuel supply to the gas turbine negatively affects the system efficiency, even though it may lead to power augmentation of the hybrid system. The efficiency reaches nearly 70% with FCT of 1000 °C, which is about 10 percent points increase from the efficiency of the SOFC only system. The voltage increase due to the pressurization is 0.027 V, which contributes to the system efficiency upgrade by about 1.2 percent point. The remaining far larger part of the efficiency improvement is due to the hybridization. The higher FCT guarantees higher efficiency of the hybrid system as in the SOFC only system. In addition, the efficiency gap increases as TIT increases.

Results for ΔT_{cell} of 100 °C are shown in Fig. 7. Variations of the SOFC power can be explained in terms of the air bypass,

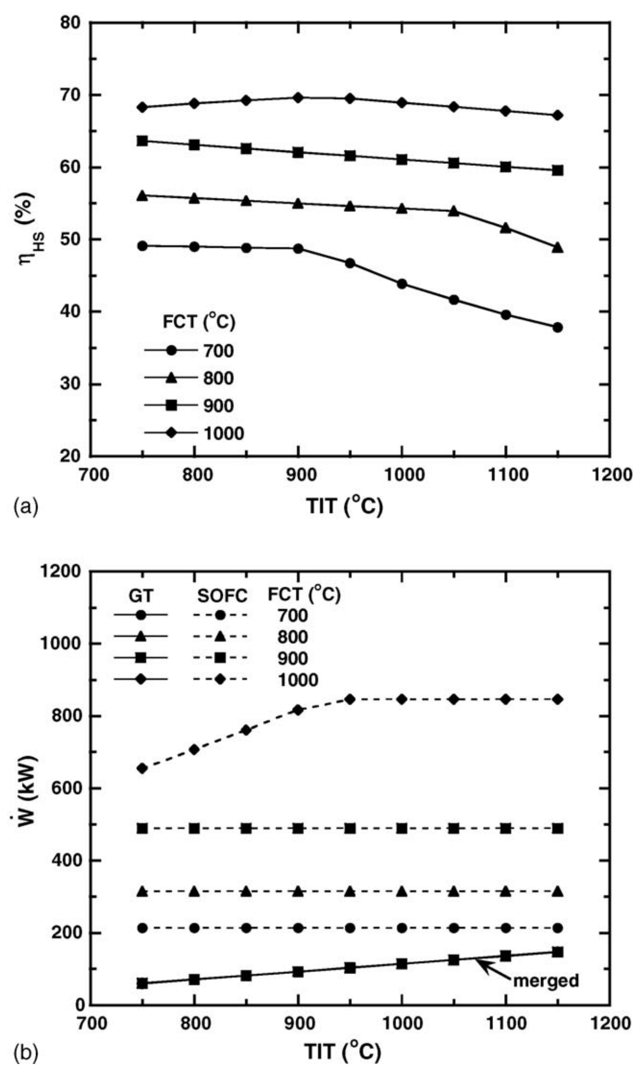

Fig. 7. Performance of configuration A with ΔT_{cell} of 100 °C: (a) system efficiency and (b) SOFC and GT power.

as in the previous case. Since most of the design conditions do not required the air bypass as shown in Fig. 4, the SOFC power remains nearly constant once FCT is fixed. Even in this smaller ΔT_{cell} case, system efficiency is over 60% for FCT of 900 °C and approaches 70% for FCT of 1000 °C. However, the efficiency is generally lower than the previous case (ΔT_{cell} = 200 °C) because the reduced ΔT_{cell} requires more additional fuel supply to the combustor to maintain an equivalent TIT. The efficiency reduces more severely as FCT decreases.

In case of the system with external reforming (configuration B), the additional fuel supply is required for all the design conditions and the air bypass is not conducted. Since the external reforming requires heat transfer from the cathode exit gas, the temperature of the gas after the heat exchanger is too low, and thus much fuel should be provided to the combustor in order to meet the required TIT. Fig. 8 shows the additional fuel supply ratio. For all conditions, the additional fuel supply ratio is

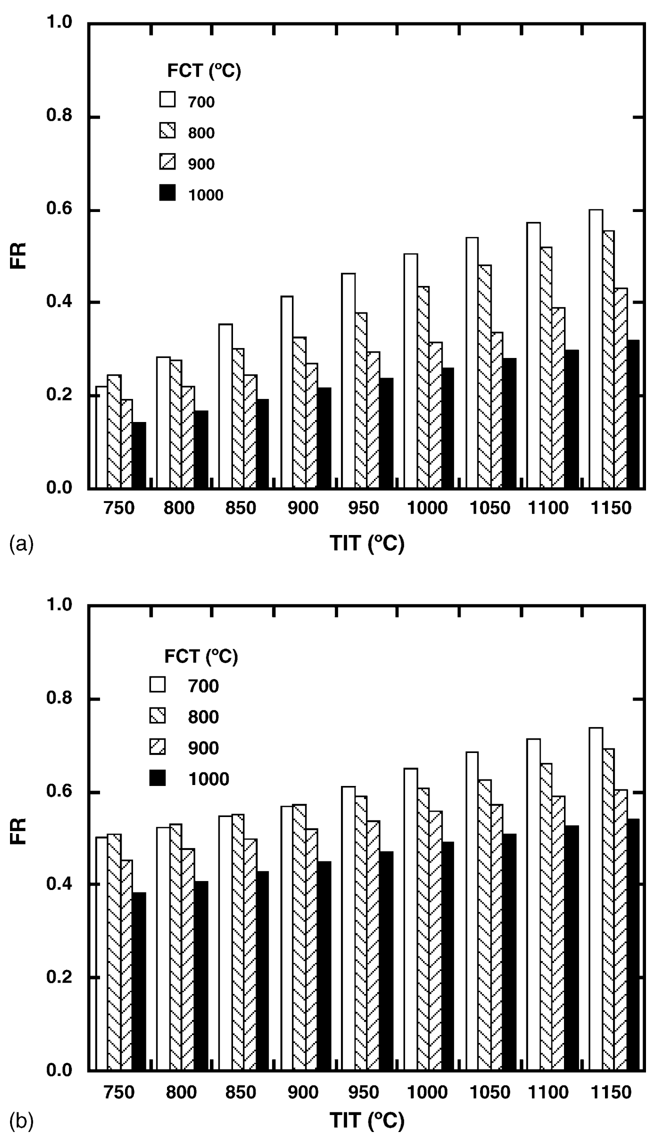

Fig. 8. Additional fuel supply ratio of configuration B: (a) ΔT_{cell} of 200 °C and (b) ΔT_{cell} of 100 °C.

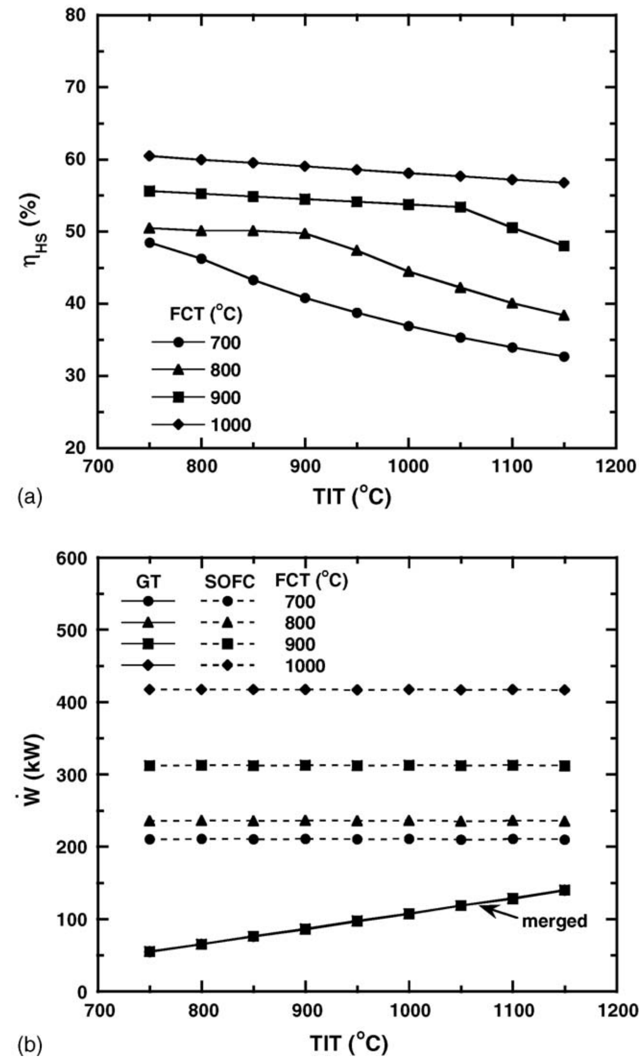

Fig. 9. Performance of configuration B with ΔT_{cell} of 200 °C: (a) system efficiency and (b) SOFC and GT power.

far greater than that of the internally reformed system. Again, the smaller ΔT_{cell} for a given FCT requires more fuel supply to the combustor to obtain the same TIT. The required recuperator effectiveness, not shown here, is very similar to that of Fig. 5 for every design condition.

The performance parameters of configuration B are shown in Figs. 9 and 10. The SOFC power remains nearly constant for a fixed FCT, because air is not bypassed after the compressor. The SOFC power, and thus the total power, is much smaller than that of the internally reformed system. The power ratio ranges from 1.5 to 8.0 for ΔT_{cell} of 200 °C and from 0.75 to 4.0 for ΔT_{cell} of 100 °C, which means that the power portion of SOFC is much smaller than that of the internally reformed system. Efficiency patterns are similar to those of the internally reformed system. However, the efficiency levels are far lower than those of the internally reformed system. These results attribute to the reduced power ratio. Reduction of the power portion of the SOFC, which is more efficient than the gas turbine, reduces the hybrid system efficiency. Even for a relaxed design option (ΔT_{cell} = 200 °C),

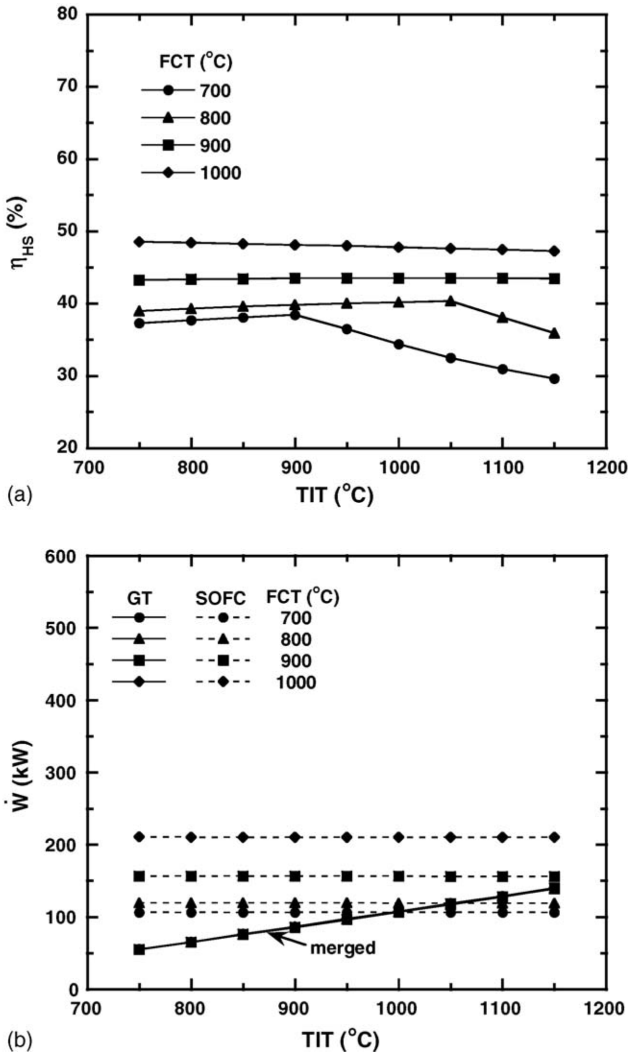

Fig. 10. Performance of configuration B with ΔT_{cell} of 100 °C: (a) system efficiency and (b) SOFC and GT power.

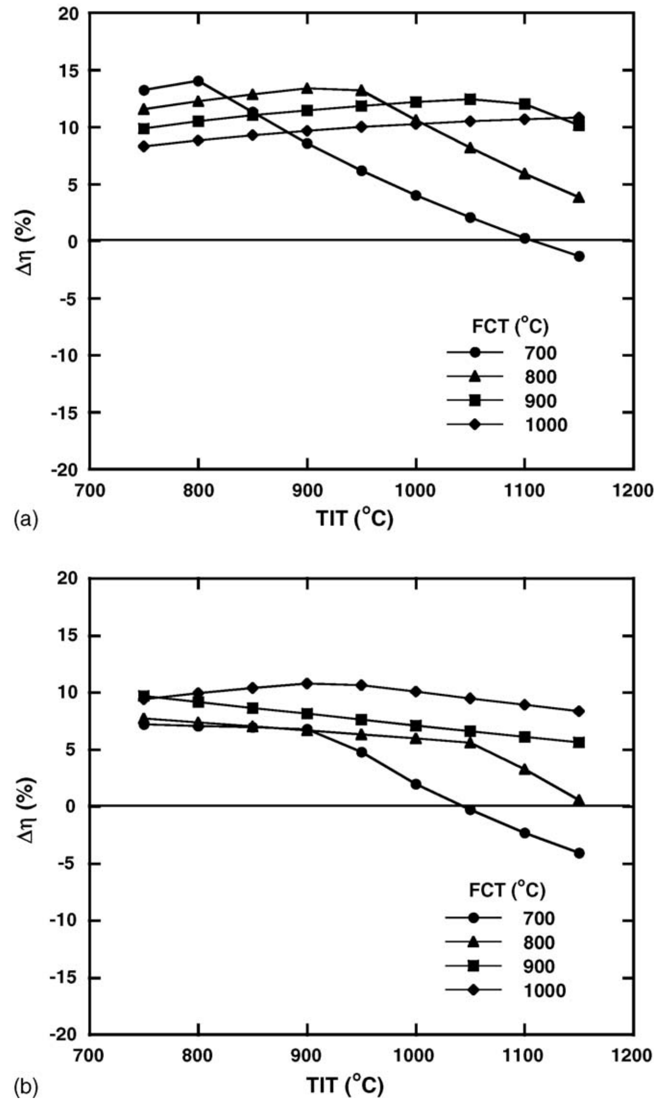

Fig. 11. Efficiency gain of hybrid system over SOFC only system, based on internal reforming: (a) ΔT_{cell} of 200 °C and (b) ΔT_{cell} of 100 °C.

system efficiency for the highest FCT cannot go beyond 60%. This is about 10 percent points less than the efficiency level of the internally reformed case. Considering that the efficiency gap between the internally and externally reformed SOFC only systems is less than 3% for FCT of 1000 °C (Fig. 2), the efficiency gap for the hybrid systems is considerably large. As the ΔT_{cell} becomes smaller, the efficiency penalty becomes more evident. For ΔT_{cell} of 100 °C, the externally reformed system gives maximum efficiency of less than 50% even with FCT of 1000 °C. The SOFC power is even smaller than that of GT in some design range (low FCT and high TIT), where the system efficiency is very low. Consequently, it can be concluded that the design performance of the externally reformed system is more susceptible to the cell design constraint and experiences far greater performance penalty as the temperature difference at the cell becomes smaller.

Figs. 11 and 12 present efficiency gains of the hybrid systems over the SOFC only systems. The efficiency gain is defined by the absolute percentage enhancement as follows:

$$\Delta\eta = \eta_{\text{HS}} - \eta_{\text{FS}} \tag{23}$$

The subscript FS signifies predictions for SOFC only systems (not the performance of the fuel cell as a part of the hybrid system), of which results have been shown in Fig. 2. With ΔT_{cell} constraint of 200 °C, efficiency gain of the internally reformed hybrid system is over 10 percent points above that of the internally reformed SOFC only system for most of the design conditions. In case of a smaller ΔT_{cell}, the efficiency gain is generally smaller than that in a case of a larger ΔT_{cell}, but still 5–10 percent points gain is possible. On the contrary, hybridization based on the external reforming does not always ensure efficiency upgrade over the SOFC only system. Efficiency gain is limited to a very small design range. For a wide design range, the hybrid system is less efficient than the SOFC only system. This is more evident for the case with a smaller ΔT_{cell}.

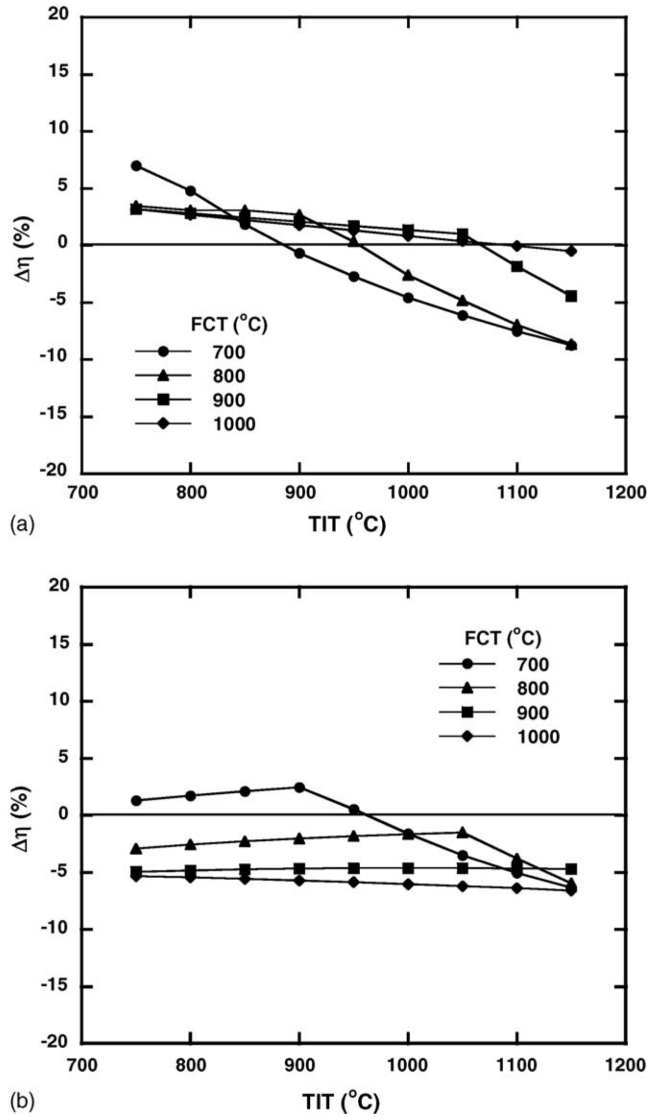

Fig. 12. Efficiency gain of hybrid system over SOFC only system, based on external reforming: (a) ΔT_{cell} of 200 °C and (b) ΔT_{cell} of 100 °C.

5. Conclusions

Performances of pressurized SOFC/GT hybrid systems with internal and external reforming have been comparatively analyzed for various combinations of fuel cell and turbine inlet temperatures, focusing on the influence of the design constraint of the temperature difference at the cell on the system performance.

In the system with internal reforming, air should be bypassed to the turbine side or fuel should be additionally supplied to the combustor, depending on the relative magnitude of the cell temperature and the turbine inlet temperature. For a fixed cell temperature, an optimal efficiency condition exists at around the conversion point between the two options (air bypass and additional fuel supply). In the system with external reforming, much more additional fuel, which is the main cause of relatively lower system efficiency, should be supplied for all the design conditions considered.

A larger temperature difference at the cell increases SOFC power and higher system efficiency. As the temperature difference at the cell decreases, additional fuel supply increases. This generally reduces the system efficiency. The advantage of the internal reforming in terms of efficiency is more evident in the hybrid system than in the simple SOFC only system. Moreover, the system efficiency of the internally reformed hybrid system is less sensitive to the design constraint of the temperature difference at the cell. The hybrid system with internal reforming shows considerable efficiency gain over the SOFC only system, whereas the system with external reforming shows far less efficiency gain. It is concluded that the internal reforming results in far better performance with the same design parameters and constraints.

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References

[1] J. Larminie, A. Dicks, Fuel Cell Systems Explained, second ed., John Wiley & Sons Ltd., New York, 2003 (Chapter 7).
[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 Turbines Power 124 (2002) 845–849.
[3] S.E. Veyo, W.L. Lundberg, S.D. Vora, K.P. Litzinger, Tubular SOFC hybrid power system status, in: ASME Paper GT2003-38943, 2003.
[4] L. Magistri, M. Bozzolo, O. Tarnowski, G. Agnew, A.F. Massardo, Design and off-design analysis of a MW hybrid system based on Rolls-Royce integrated planar SOFC, in: ASME Paper GT2003-38220, 2003.
[5] G.D. Agnew, J. Townsend, R.R. Moritz, M. Bozzolo, S. Berenyi, R. Duge, Progress in the development of a low cost 1 MW SOFC hybrid, in: ASME Paper GT2004-53350, 2004.
[6] M.C. Williams, J.P. Strakey, S.C. Singhal, U.S. distributed generation fuel cell program, J. Power Sources 131 (2004) 79–85.
[7] S.P. Harvey, H.J. Richter, Gas turbine cycles with solid oxide fuel cells. Part I: improved gas turbine power plant efficiency by use of recycled exhaust gases and fuel cell technology, Trans. ASME J. Energy Resour. Technol. 116 (1994) 305–311.
[8] D.J. White, Hybrid gas turbine and fuel cell systems in perspective review, in: ASME Paper 99-GT-419, 1999.
[9] E.A. Liese, R.S. Gemmen, Performance comparison of internal reforming against external reforming in a SOFC, gas turbine hybrid system, in: ASME Paper GT 2003-38566, 2003.
[10] S. Kimijima, N. Kasagi, Performance evaluation of gas turbine–fuel cell hybrid micro generation system, in: ASME Paper GT-2002-30111, 2002.
[11] D. Bohn, N. Poppe, J. Lepers, Assessment of the potential of combined micro gas turbine and high temperature fuel cell systems, in: ASME Paper GT-2002-30112, 2002.
[12] S. Campanari, Parametric analysis of small scale recuperated SOFC/gas turbine cycles, in: ASME Paper GT2004-53933, 2004.
[13] 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 a micro gas turbine, J. Power Sources 96 (2001) 352–368.
[14] T. Tsuji, N. Yanai, K. Fujii, H. Miyamoto, M. Watabe, T. Ishiguro, Y. Ohtani, H. Uechi, Multi-stage solid oxide fuel cell: gas turbine combined cycle hybrid power plant system, in: ASME Paper 2003-GT-38391, 2003.

[15] A. Selimovic, J. Palsson, Networked solid oxide fuel cell stacks combined with a gas turbine cycle, J. Power Sources 106 (2002) 76–82.

[16] Y.J. Yang, T.S. Kim, J.H. Kim, Performance characteristics analysis of gas turbine-pressurized SOFC hybrid systems, Kor. J. Air-Cond. Ref. Eng. 16 (2004) 615–622.

[17] G.D. Agnew, M. Bozzolo, R.R. Moritz, S. Berenyi, The design and integration of the Rolls-Royce fuel cell systems 1 MW SOFC, in: ASME Paper GT2005-69122, 2005.

[18] 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 Turbines Power 122 (2002) 27–35.

[19] EG & G Service Parson Inc., Fuel Cell Handbook, fifth ed., 2000 (Chapter 8).

[20] Aspen Technology Inc., HYSYS ver. 3.2, 2004.