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Comparison between pressurized design and ambient pressure design of hybrid solid oxide fuel cell–gas turbine systems

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Abstract

Design performances of the hybrid solid oxide fuel cell (SOFC)–gas turbine (GT) system have been investigated. A pressurized system and an indirectly heated ambient pressure system were analyzed and their performances were compared. In the baseline layout, the basic performance characteristics of the two system configurations were analyzed, with the cell operation temperature and the pressure ratio as the main design parameters. The pressurized system exhibits a better efficiency owing to not only the higher cell voltage but also more effective utilization of gas turbine, i.e., a larger GT power contribution due to a higher turbine inlet temperature. Independent setting of the turbine inlet temperature was simulated by using the additional fuel supply as well as the air bypass. Increasing the pressure ratio of the gas turbine hardly improves the system efficiency, but the efficiency becomes less sensitive to the turbine inlet temperature. In the ambient pressure system, the available design parameter range is much reduced due to the limit on the recuperator temperature. In particular, design of the ambient pressure hybrid system with a gas turbine of a high pressure ratio does not seem quite feasible because the system efficiency that can be achieved at the possible design conditions is even lower than the efficiency of the SOFC only system.

Keywords: Solid oxide fuel cell; Gas turbine; Pressurized hybrid system; Ambient pressure hybrid system

1. Introduction

Due to rapid decrease of energy resources as well as increase of environmental issues, the need for efficient and environment friendly energy devices has been increasing steadily. In particular, development of advanced power generation systems has become very important because the electric power industry is the biggest primary energy consuming sector. Among other developments, high temperature fuel cells such as solid oxide fuel cells and molten carbonate fuel cells are being considered as the most promising stationary electric power sources. In particular, the solid oxide fuel cell (SOFC) is suitable for hybridization with the gas turbine (GT) because it has a wide operating temperature range (600–1000 °C). Starting from a short-term target of sub-MW class, leading countries are ultimately aiming to develop multi-MW systems for distributed generation [1,2]. Conceptual designs of even larger systems for electric power stations (hundreds of MW) are also being considered [3].

Since the hybrid system consists of two parts, which are totally different in nature, and requires diverse balance-of-plant components, various critical factors should be reviewed prior to its design. The most important factors are the fuel reforming method and the system configuration. The steam reforming is most common in stationary applications due to its high conversion efficiency. A few recent studies have focused on the influence of the reforming heat source on system performance [4,5]. General conclusion of these studies is that the internal reforming allows better system performance than the external reforming. In addition, a more fundamental factor to consider in the early design stage of a hybrid system is the operating pressure of the fuel cell [6]. Fuel cells can be designed to operate either at an ambient pressure (ambient pressure system) or at an elevated pressure (pressurized system). In a pressurized system, the high pressure air from the compressor is delivered directly to the fuel cell and the outgoing high pressure gas drives the turbine. In an ambient pressure system, the fuel cell is driven by the air (or gas) discharged from the turbine. The advantage

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Nomenclature

F	Faraday constant (96,486 C mol^{-1})
FCT	fuel cell temperature (°C)
GT	gas turbine
$\bar{h}$	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})
PF	power fraction
PR	pressure ratio
$\dot{Q}$	heat transfer rate (kW)
RIGT	recuperator inlet gas temperature (°C)
SOFC	solid oxide fuel cell
T	temperature (°C)
ΔT_c	temperature difference at the fuel cell (°C)
TIT	turbine inlet temperature (°C)
V	voltage (V)
$\dot{W}$	power (kW)

Greek letter

η	efficiency, effectiveness

Subscripts

AC	alternating current
AUX	auxiliary
c	cell
C	compressor
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
out	outlet
r	reformer
rec	recuperator
T	turbine

of the pressurized system is the possibility of a high cell voltage (thus high cell performance) and a compact design, and the advantage of the ambient pressure system is that the gas turbine pressure is uncoupled from the cell pressure, so the gas turbine pressure can be selected over a wide range. Until now, pressurized hybrid SOFC systems have been developed [7,8], but the need for developing ambient pressure hybrid SOFC systems has also been recognized because developers have experienced some critical problems in designing and operating the early versions of the pressurized system (system complexity, difficulty in matching SOFC and GT, etc.) [9].

Accordingly, in this study, the pressurized system and the ambient pressure system are analyzed and their performance characteristics are critically compared. In this study, three temperatures (fuel cell operating temperature, temperature difference at the cell, and turbine inlet temperature) are considered as the main design parameters. For a reasonable performance comparison, consistent assumptions have been applied to these parameters. Most hybrid systems currently under development use small gas turbines designed at a low pressure ratio. With the introduction of advanced medium size (MW class) gas turbines into the market [10], the hybridization of these gas turbines with SOFC has also been reviewed [11]. To cover the different gas turbine specifications, a wide pressure ratio range is examined in this study. Two stepwise analyses are performed. Firstly, the performance of the baseline layout is analyzed. Secondly, the matched design of the fuel cell and the gas turbine parameters are analyzed.

2. System configurations

Fig. 1 shows the two different hybrid system configurations analyzed in this study. The SOFC module, which includes a cell stack, a reformer, an afterburner and a preheater, is common in both systems. The major difference is the working pressure of the SOFC module. The internal reforming is adopted, and the steam required for the reforming reaction is supplied through the anode gas recirculation. The remaining fuel after the cell stack is combusted at the afterburner, and the incoming air to the cathode is heated at the preheater to meet the required cathode inlet temperature. In the pressurized system, the compressor exit air is heated at the recuperator and supplied to the SOFC module, where air is further heated as explained above. The high pressure gas from the SOFC module drives the turbine. This system is conceptually similar to that used in the demonstration plant of Siemens-Westinghouse [7]. In designing the hybrid system based on the SOFC operating at an ambient pressure, a few options exist regarding the method of obtaining a high temperature at the turbine inlet. In the ambient pressure system adopted in this study, the pressurized high temperature air after the recuperator directly drives the turbine and then the expanded air flows into the SOFC module. This type of system is called an indirectly heated system because the high temperature at the turbine inlet is not achieved by combustion but by heating. The combustor drawn by the dotted line is a supplementary element used for additional fuel supply as will be explained later. This kind of indirectly heated configuration is the most natural way to construct the ambient pressure system [9]. The concept of indirect heating has also been adopted in the molten carbonate fuel cell/gas turbine hybrid system [12], where the remaining fuel after the cell is combusted with the air exhausted from the turbine and then the high temperature gas heats the air, preheated at the primary recuperator, to the turbine inlet temperature at the secondary recuperator [12]. Direct heating (firing) of the turbine, where the anode gas is boosted to the turbine inlet pressure and combusted before the turbine, has also been suggested for the molten carbonate fuel cell hybrid system [13]. With the direct heating, the molten carbonate fuel cell hybrid system was

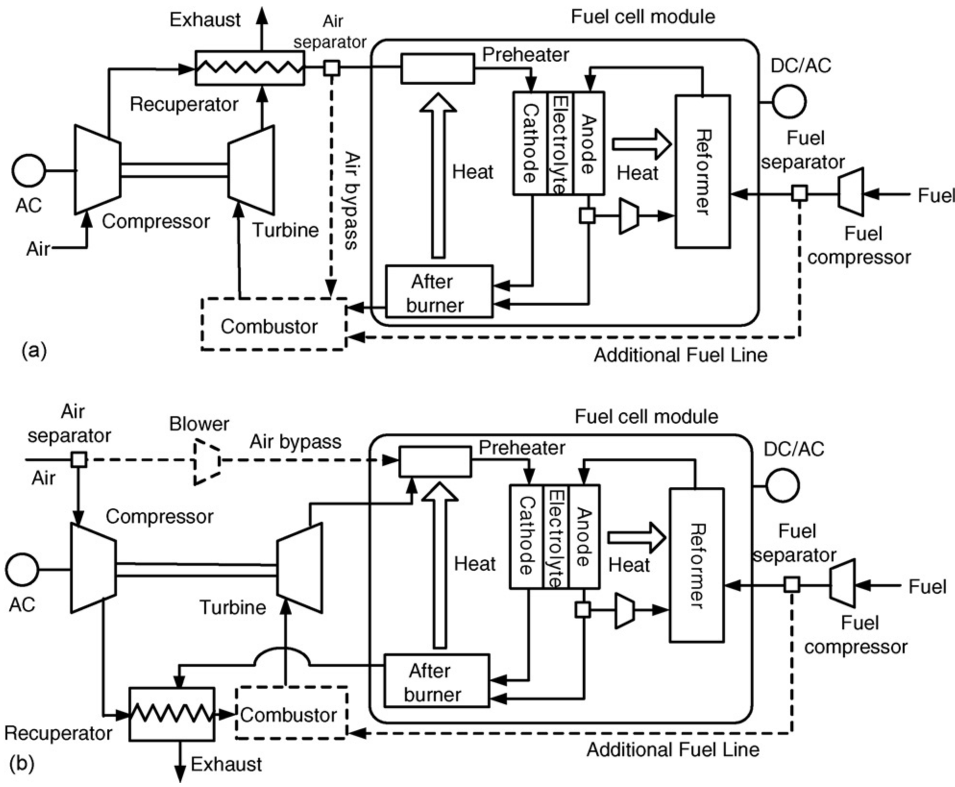

Fig. 1. Hybrid system configurations: (a) pressurized system and (b) ambient pressure system.

evaluated to have a higher efficiency than the indirectly heated system [13]. Adoption of the additional (secondary) recuperator or the direct heating is feasible in the molten carbonate fuel cell hybrid system that operates at a relatively low temperature (around 650 °C). However, in the SOFC environment (maximum 1000 °C), these configurations are not very feasible because the operating temperatures of the additional components, such as the heat exchanger and the anode gas booster, may be far higher than the practical temperature limit of state-of-the-art technology materials. Consequently, the current system configuration of Fig. 1(b), where the exit gas from the SOFC module heats up the recuperator, is selected as the representative ambient pressure system configuration.

The dotted lines shown in both configurations represent the additional fuel supply and the air bypass, respectively. They are optional functions adopted only when the turbine inlet temperature (TIT) needs to be assigned independently of the fuel cell operating temperature (FCT), as was demonstrated in the previous study [5]. By modulating the amounts of the additional fuel supply and the air bypass, various combinations of the two main temperatures are possible and their effect on the hybrid system performance can be investigated. These functions are important in the second part of the analysis of this study.

3. Modeling and analysis

Each component is modeled as a lumped control volume. The fuel is methane and is supplied to the SOFC module. At the reformer, steam reforming and water gas shift are assumed to occur at equilibrium. The amount of the steam supplied to the reformer is decided by the steam carbon ratio, which is defined as the molar ratio between the supplied steam to the cell and the supplied methane. Both hydrogen and carbon monoxide generated by the steam reforming process participate in the electrochemical reaction. The fuel utilization factor at the cell is defined as the molar ratio between the reacted fuel and the supplied fuel at the cell (hydrogen and carbon monoxide).

The cell voltage is a major parameter that determines the cell performance and usually depends on the operating pressure and temperature of the fuel cell. It also depends on the cell material and structure (geometry). Since this study does not consider a specific fuel cell, a simplified approach is used. A reasonable reference value is given for the nominal design condition (0.7 V at 800 °C and 3.5 bar), and its variation according to the cell operating temperature and pressure is assumed based on published correlations. Since this study intends to perform a design analysis, the current density of the unit cell is assumed to be constant for all cases. Therefore, different powers obtained from the analysis can be realized by different cell stack size (e.g., number of stacked cells). Given a nominal value, a published correlation [14] is used to simulate the dependence of the cell voltage on the fuel cell temperature. The voltage increases as the operating temperature of the fuel cell increases. The cell voltage also intensifies as the operating pressure of the fuel cell increases. This effect is modeled by a published pressure dependent correlation [15]. Based on the cell voltage, the DC power of the SOFC stack is calculated as follows:

$$\dot{W}_{FC,DC} = VI = V(\dot{n}_{H_2} + \dot{n}_{CO})_{reacted} 2F \quad (1)$$

The final AC power from the SOFC is calculated as follows, considering the DC to AC conversion loss and the auxiliary power consumption such as the recirculation blower power.

$$\dot{W}_{FC,AC} = \dot{W}_{FC,DC}\eta_{conv} - \dot{W}_{AUX} \tag{2}$$

The energy balances at the cell and the reformer are presented by the following equations:

Cell:

$$\sum_{in}\dot{n}_i\bar{h}_i + \dot{Q}_c = \sum_{out}\dot{n}_i\bar{h}_i + \dot{W}_{FC,DC}, \quad \text{where} \quad \dot{Q}_c < 0. \tag{3}$$

Reformer:

$$\sum_{in}\dot{n}_i\bar{h}_i + \dot{Q}_r = \sum_{out}\dot{n}_i\bar{h}_i, \quad \text{where} \quad \dot{Q}_r = -\dot{Q}_c \tag{4}$$

The temperature difference (rise) at the cell is defined as follows:

$$\Delta T_c = \text{FCT} - \text{cathode inlet temperature} \tag{5}$$

In general, for a fixed FCT, the performance of the fuel cell becomes higher (larger power in particular) as the cathode inlet temperature is lowered [5]. However, too large a temperature difference at the cell would cause mechanical problems because of the large thermal stress evolution inside the cell. Therefore, a performance comparison among various design conditions is meaningful only when a consistent temperature difference at the cell is assumed. Consequently, the cell temperature difference is a major independent design parameter in this study.

The gas turbine power is calculated as follows, considering mechanical and generator losses and the auxiliary power consumption such as the fuel compressor power:

$$\dot{W}_{GT,AC} = (\dot{W}_T\eta_m - \dot{W}_C)\eta_{gen} - \dot{W}_{AUX} \tag{6}$$

Consequently, the net hybrid system power and efficiency are calculated as follows:

$$\dot{W}_{HS} = \dot{W}_{FC,AC} + \dot{W}_{GT,AC} \tag{7}$$

$$\eta_{HS} = \frac{\dot{W}_{HS}}{(\dot{m}\text{LHV})_{CH_4}} \tag{8}$$

The power fraction of the gas turbine is defined by the following ratio:

$$\text{PF}_{GT} = \frac{\dot{W}_{GT,AC}}{\dot{W}_{FC,AC} + \dot{W}_{GT,AC}} \tag{9}$$

Process simulation software [16] was used for the analysis. Assumed main component parameters are shown in Table 1. Standard ambient condition (15 °C, 101.3 kPa) was assumed. The air flow rate to the SOFC module was set to 1.0 kg s^{-1} for all cases. Reasonable pressure losses of 0.5–3% were assumed for every flow element. Since this study intends to analyze thermodynamic performance of the entire system, any particular heat transfer mechanism is not assumed for the heat exchange processes such as the air heating at the recuperator and the preheater, and the heat transfer between the cell and the reformer.

Table 1
Major component parameters

Fuel cell	
Steam to carbon ratio	3.0
Utilization factor	0.7
DC to AC conversion efficiency	0.93
Gas turbine and others	
Compressor efficiency	0.78
Turbine efficiency	0.85
Mechanical efficiency	0.96
Generator efficiency	0.93
Reference recuperator effectiveness	0.83

4. Results and discussion

4.1. Baseline design

‘Baseline’ means that two optional functions such as the additional fuel supply and the air bypass (dotted lines of Fig. 1) are not adopted. There are three major temperature parameters: the turbine inlet temperature, the fuel cell temperature, and the temperature difference at the cell (or cathode inlet temperature). Without the optional functions, all of these three parameters cannot be assigned simultaneously. Only two of them can be selected as independent parameters and the remaining parameter is obtained from the analysis. In this section, the FCT and the ΔT_c are given as the independent design parameters and the turbine inlet temperature is determined from the analysis. On the gas turbine side, the pressure ratio is another independent design parameter. Two different values of the ΔT_c (200 and 100 °C) are assumed to examine the effect of the severity of the fuel cell constraint on system performance.

Fig. 2 presents the result of the pressurized system for the ΔT_c = 200 °C. Fig. 2(a) shows the variation in the hybrid system efficiency and Fig. 2(b) shows the corresponding turbine inlet temperature and power fraction of the gas turbine. For a given FCT, increasing the pressure ratio tends to decrease the turbine exit temperature. Thus, the recuperator exit air temperature decreases. Since the ΔT_c is equivalent in all cases, a lower recuperator exit temperature means that greater heat is required at the preheater. This results in a reduced turbine inlet temperature. Therefore, the increasing pressure ratio for a fixed FCT lowers the TIT. In the pressurized system, a higher pressure at the SOFC allows a higher cell voltage, which enhances the SOFC power. Fig. 3 provides an example of the cell voltage for both the pressurized system and the ambient pressure system. The voltage increases with increasing gas turbine pressure ratio (i.e., higher SOFC pressure) in the pressurized system, but remains constant in the ambient pressure system. The power contribution of the gas turbine generally decreases with increasing pressure ratio because the TIT decreases. The gas turbine power fraction remains less than 15% and decreases as the FCT increases. The efficiency has a peak, but does not strongly depend on the pressure ratio. In the high pressure ratio range (over six) for the

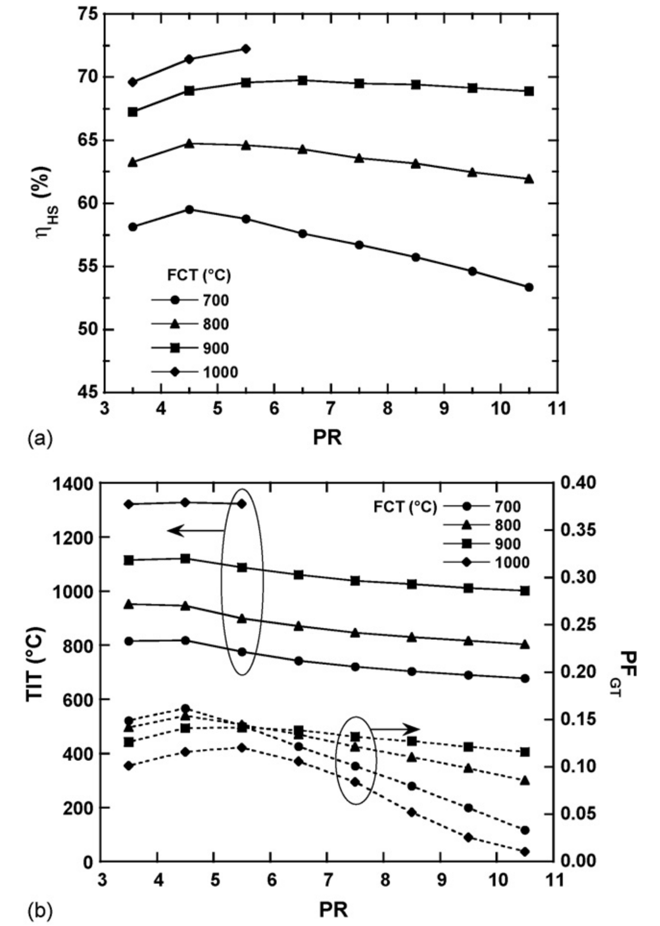

Fig. 2. Performance of the pressurized hybrid system with the ΔT_c of 200 °C: (a) system efficiency and (b) turbine inlet temperature and gas turbine power fraction.

highest FCT (1000 °C), the oxygen content at the cathode exit is not enough to burn all the redundant fuel at the afterburner, so the TIT will decrease rapidly. Thus, that region is excluded from the practical design range.

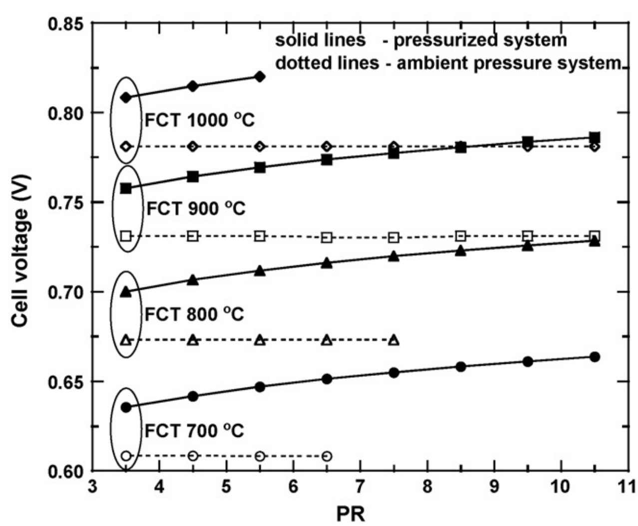

Fig. 3. Variation of cell voltage.

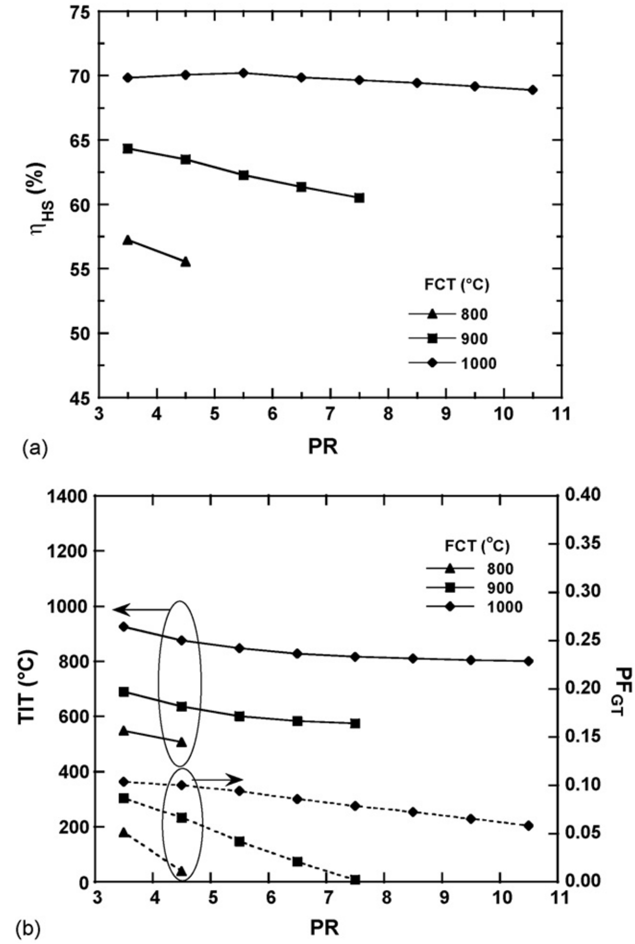

Fig. 4. Performance of the pressurized hybrid system with the ΔT_c of 100 °C: (a) system efficiency and (b) turbine inlet temperature and gas turbine power fraction.

Fig. 4 shows the results for the ΔT_c of 100 °C. For a given FCT, a smaller ΔT_c reduces the fuel supply to the cell because the cathode inlet air temperature rises. Accordingly, the cell power reduces for the same air flow rate. In this example, the SOFC power with the ΔT_c of 100 °C is roughly half of that of the case with the ΔT_c of 200 °C. The higher cathode inlet air temperature at a smaller ΔT_c requires larger heat transfer from the high temperature gas to the air at the preheater. Therefore, the TIT is much lower than that of the larger ΔT_c case. With 100 °C reduction of the ΔT_c, the average decrease of TIT is about 400 °C. This lower TIT reduces the gas turbine power fraction. It also affects the available design range considerably. If the TIT is too low, the gas turbine does not produce a net positive power output. Thus, the high pressure ratio region for each FCT condition is excluded as shown in figure. As the FCT decreases, the possible design range shrinks considerably. Compared with the larger ΔT_c case, total system power is smaller and the efficiency is lower due to relatively smaller contribution of the gas turbine power resulting from the lower TIT.

Fig. 5 shows results for the ambient pressure system with the ΔT_c of 200 °C. Due to the indirect heating of the turbine inlet air, the TIT tends to be lower than that of the pressurized system. A lower TIT leads to a lower turbine exit temperature,

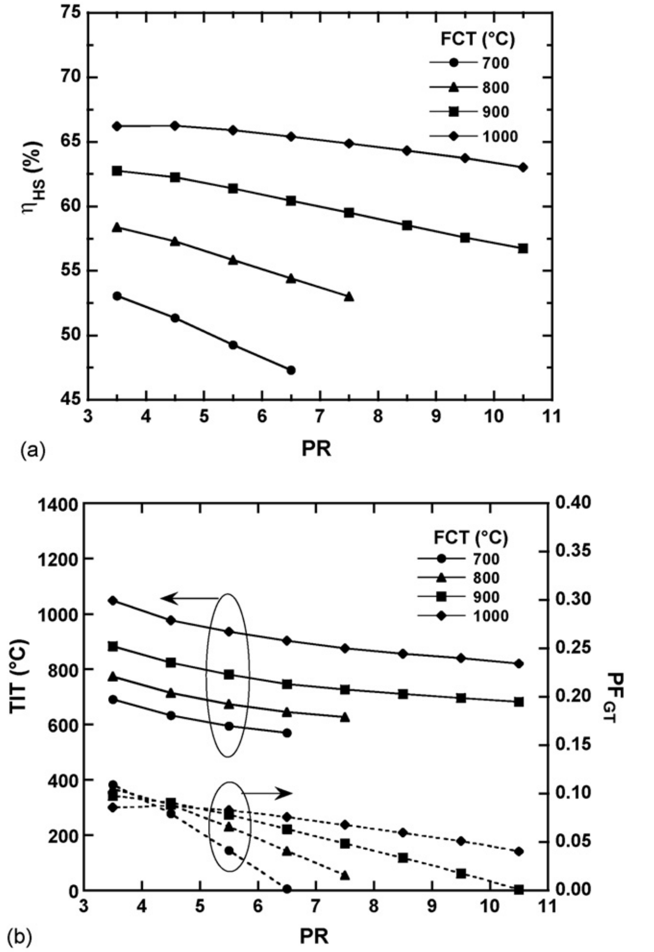

Fig. 5. Performance of the ambient pressure hybrid system with the ΔT_c of 200 °C: (a) system efficiency and (b) turbine inlet temperature and gas turbine power fraction.

which in turn accelerates the TIT reduction because more heat of the SOFC exit gas is consumed at the preheater to maintain the same cathode inlet temperature, i.e., the same ΔT_c. Similar to the smaller ΔT_c case of the pressurized system, the high pressure ratio region of low FCTs does not allow a hybrid system design because the gas turbine cannot produce a net positive power output. The TIT is much lower than that of the pressurized system at the same FCT. The resulting smaller power contribution of the gas turbine in the ambient pressure system is the main cause of the lower system efficiency compared with the pressurized system. Furthermore, the system efficiency decreases more rapidly with increasing pressure ratio.

If the design ΔT_c is set to 100 °C in the ambient pressure system, the amount of fuel available at the after burner reduces and thus, the TIT becomes too low to generate a net positive power in most design conditions. Net positive gas turbine power is available only in a very limited range of high FCTs and low pressure ratios and moreover, the performance improvement by hybridization is very small. Therefore, results are not shown here. In conclusion, if the SOFC stack is to be designed with a small temperature difference at the cell, the ambient pressure hybrid system with the baseline layout is not feasible.

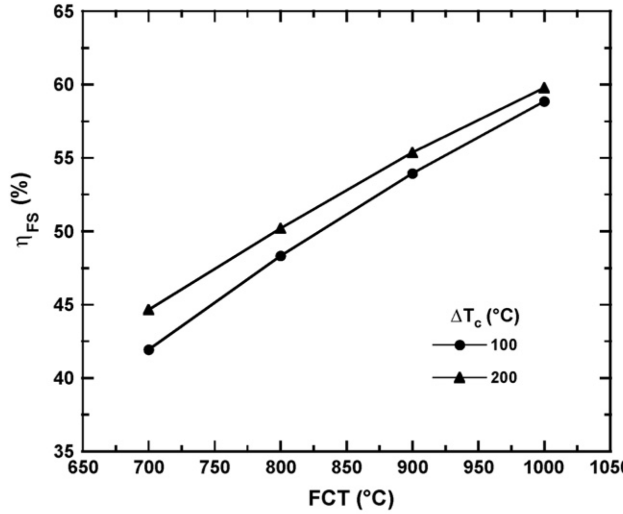

Fig. 6. Efficiency of the SOFC only system.

The advantage of the hybrid system can best be illustrated by comparing its performance with that of the SOFC only system. Accordingly, the performance of the SOFC only system needs to be described separately. The efficiency of the SOFC only system is shown in Fig. 6. Analysis was performed with the gas turbine part removed from the baseline layout. The SOFC stack operates at an ambient pressure. More detailed explanation can be found in the previous study [5]. The slight efficiency discrepancy between the two different cases is due to the difference in auxiliary power consumptions. The efficiency of the pressurized hybrid system is 10–15 percent point higher than that of the SOFC only system (compare Figs. 2 and 6). In particular, the efficiency upgrade is more prominent in the low FCT conditions. On the other hand, maximum efficiency improvement by the ambient pressure hybrid system is about 8 percent point for the ΔT_c of 200 °C. The ambient pressure hybrid system hardly provides any efficiency advantage over the SOFC only system for the ΔT_c of 100 °C.

From the analyses for the baseline system layouts, the following summary is possible. The pressurized system exhibits higher system efficiency than the ambient pressure system for any design conditions. The ambient pressure system is not feasible when a gas turbine of a high pressure ratio is to be utilized because turbine inlet temperature is too low.

4.2. Matching SOFC with GT

The analysis of the previous section indicates that in the baseline hybrid system, a higher pressure ratio prefers a lower turbine inlet temperature. However, in reality, the situation is quite reversed. Gas turbines designed with low pressure ratios (micro gas turbines) usually have a low TIT and more advanced gas turbines designed with a higher TIT require a high pressure ratio. Therefore, it is difficult to satisfy the design requirements of the baseline layouts of the hybrid system with the existing gas turbines. In other words, the baseline hybrid system cannot easily accommodate the design practice of gas turbines. The situation seems more severe in the ambient pressure hybrid systems because the required turbine inlet temperature of the baseline layout is too low (see Fig. 5). Consequently, a revised system layout is required to arbitrarily match a given turbine inlet temperature to the SOFC design condition. This is performed by introducing the additional fuel supply and the air bypass described by the dotted lines in Fig. 1. The performance of the pressurized hybrid system with these supplementary functions has been examined in the previous study [5]. It focused only on a specific pressure ratio and investigated the effect of different reforming methods on the hybrid system performance. This study extends the design parameter range, especially the pressure ratio, and aims to analyze both the pressurized system and the ambient pressure system and compare their performance characteristics.

With the additional functions, the three major parameters (FCT, ΔT_c and TIT) can be satisfied simultaneously. For both systems, fuel is supplied additionally to the combustor when the TIT of the baseline layout is lower than a desired value. The air bypass functions differently in the two systems. In the pressurized system, some portion of the recuperator exit air is bypassed to the turbine side if the TIT of the baseline layout is higher than the desired temperature. In the ambient pressure system, if the ΔT_c tends to be less than the assigned value (i.e., if the cathode inlet temperature tends to decrease below the desired value), some of the inlet air is bypassed from the system inlet line to the SOFC. In summary, only one of the two functions is activated in the pressurized system, while both of them can be used simultaneously in the ambient pressure system.

Since the purpose of this section is to examine the influence of the additional functions on the system performance and design characteristics, various combinations between the FCT and the TIT are examined. To exploit high fuel cell performance, high cell temperatures are assumed (900 and 1000 °C). The TIT ranges from 750 to 1150 °C, covering small to mid size gas turbines. A wide range of pressure ratios was investigated, but two representative examples will be described here as demonstrating examples: 3.5 for current micro gas turbine and 8.5 for medium size gas turbine.

The major features of using the additional functions are briefly explained before presenting the results. As the desired TIT increases, the additional fuel increases. This is common to both the pressurized and ambient pressure systems. If all the other conditions are equivalent, a higher pressure ratio and a lower FCT would require more additional fuel supply. Increasing the additional fuel supply (thus increasing TIT) increases the power fraction of the gas turbine. In the pressurized system, some of baseline designs result in a sufficiently high TIT (see Fig. 2(b)). Thus, if a moderate TIT is allowed, air should be bypassed to the turbine inlet to decrease the TIT. In the ambient pressure system, the TIT is lowered by reducing the heat addition at the recuperator (design with lower recuperator effectiveness). If the turbine exit temperature tends to exceed the desired cathode inlet temperature, usually accompanied by much additional firing, air needs to be bypassed to satisfy the desired value. The ratio of the air bypass increases as the pressure ratio decreases.

Fig. 7 shows the system efficiency and the gas turbine power fraction of the pressurized system for the pressure ratio of 3.5.

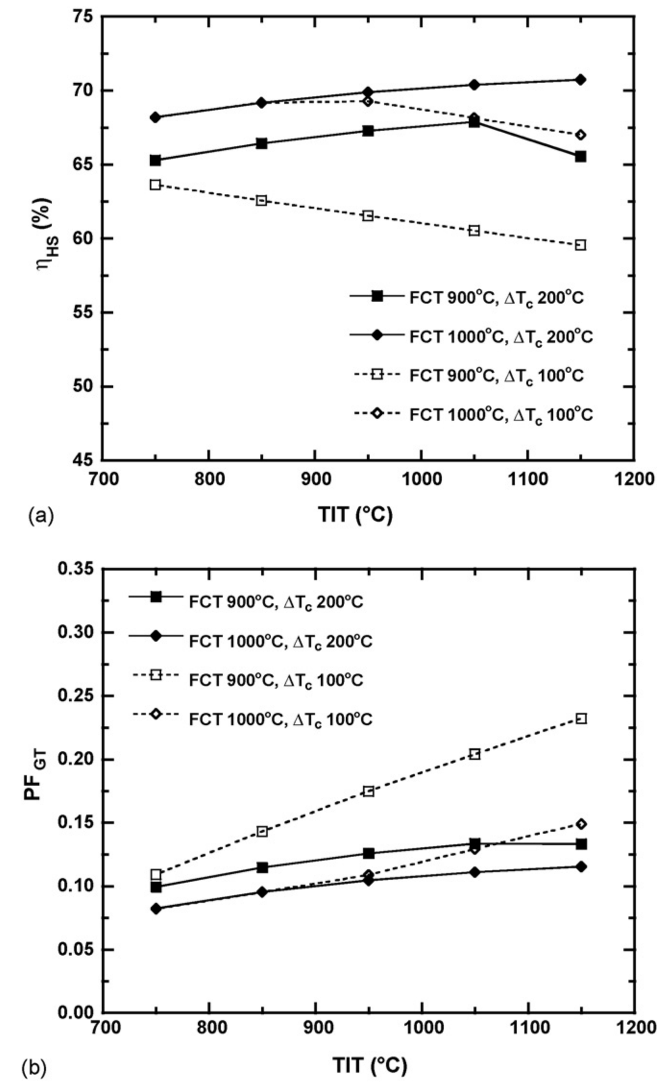

Fig. 7. Performance of the pressurized hybrid system for different combinations of the fuel cell temperature and the turbine inlet temperature (pressure ratio of 3.5): (a) system efficiency and (b) gas turbine power fraction.

With the ΔT_c of 200 °C, most of the cases require air bypass because the baseline TITs are already quite high (see Fig. 2(b)). As the ΔT_c and the FCT decrease, the additional fuel supply increases. For a fixed FCT and ΔT_c condition, a peak efficiency exists, which corresponds to the baseline case. Therefore, either the additional fuel supply (left of the peak) or the air bypass (right of the peak) decreases the system efficiency from the baseline efficiency. In some cases, the peak locates outside the TIT range of this figure. The gas turbine power fraction increases as the TIT increases. The smaller the ΔT_c and the FCT, the larger the gas turbine power fraction becomes. In some cases, the efficiency reduces moderately, while the gas turbine power fraction increases much. For the case with the FCT of 900 °C and the ΔT_c of 100 °C, the efficiency reduction is only 3.5 percent point, while the gas turbine fraction increases from 10 to 23%. Accordingly, the additional fuel supply is quite feasible even with a slight efficiency loss because the system unit cost can be reduced much by the increased portion

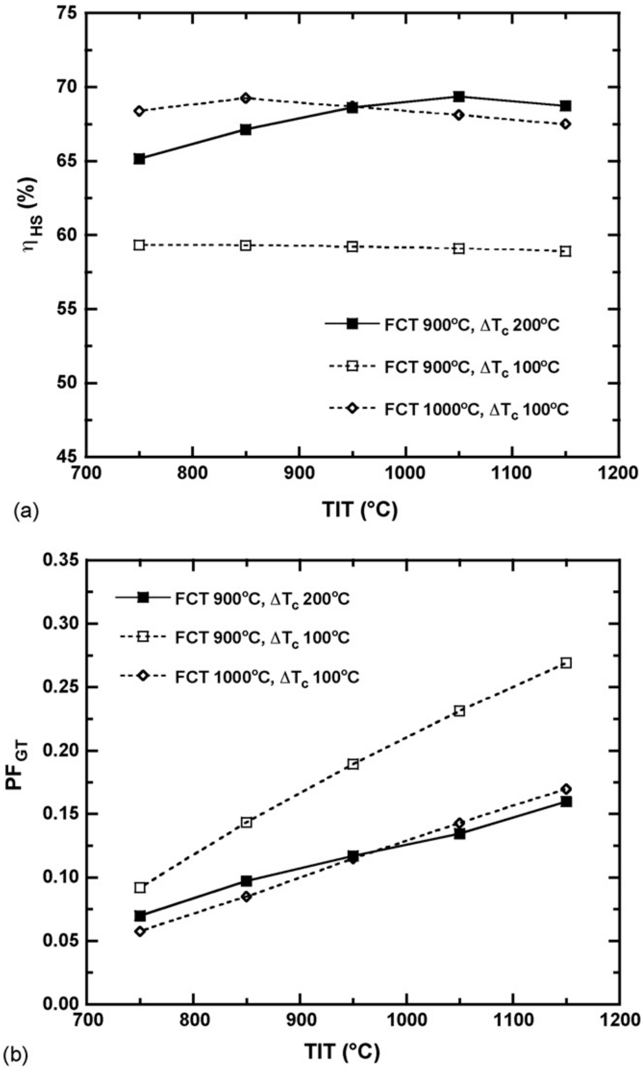

Fig. 8. Performance of the pressurized hybrid system for different combinations of the fuel cell temperature and the turbine inlet temperature (pressure ratio of 8.5): (a) system efficiency and (b) gas turbine power fraction.

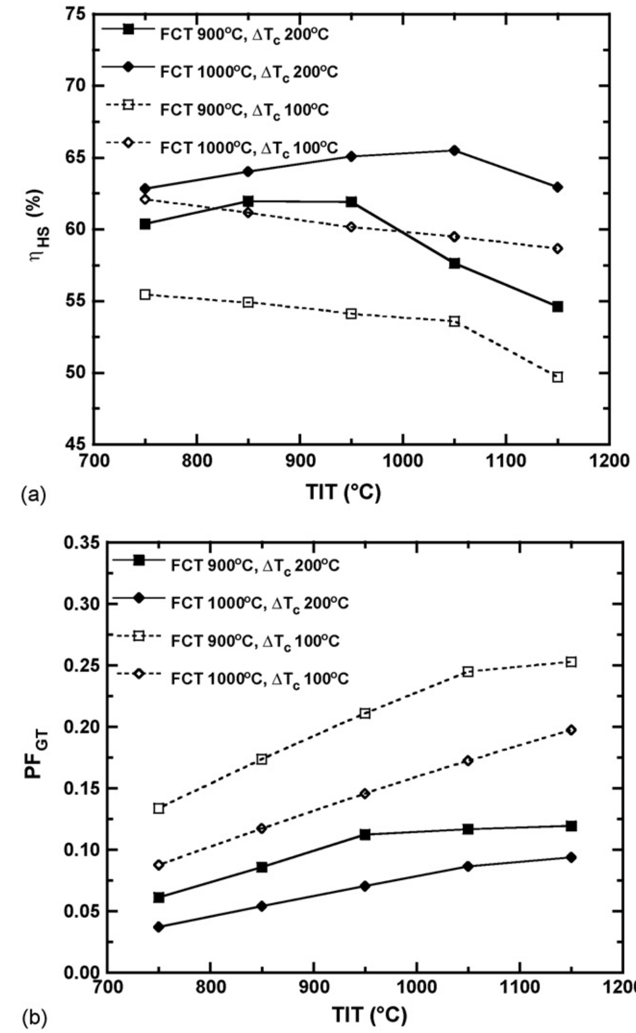

Fig. 9. Performance of the ambient pressure hybrid system for different combinations of the fuel cell temperature and the turbine inlet temperature (pressure ratio of 3.5): (a) system efficiency and (b) gas turbine power fraction.

of the gas turbine that is relatively low-priced compared with the SOFC.

Fig. 8 presents the results of the pressurized system for the pressure ratio of 8.5. The design of the highest FCT (1000 °C) case with a larger ΔT_c (200 °C) is not available for this high pressure ratio as we have seen in the baseline case (Fig. 2(a)). As in the previous case of low pressure ratio, the peak occurs at the baseline case. A slight difference is that the rate of efficiency reduction with increasing TIT is smaller than that of the low pressure ratio case. Moreover, the gas turbine power fraction is higher than that of the low pressure ratio case. Therefore, increasing TIT by the additional fuel supply is quite promising in the high pressure ratio case in terms of the manufacturing cost, mentioned at the end of the last paragraph. Furthermore, since the TIT of 1100–1200 °C exactly matches those of medium size gas turbines in the market [10], modification of the existing gas turbine can be minimized.

From the results for the pressurized hybrid systems, the following conclusion is possible. Even though the efficiency generally decreases as the TIT increases, it is still sufficiently higher than that of the SOFC only system. Using a high pressure ratio gas turbine does not improve the system efficiency (comparable or slightly lower), but the large power share by the gas turbine is an advantage in terms of the unit cost.

Figs. 9 and 10 present the results of the ambient pressure system. In Fig. 9, results for the pressure ratio of 3.5 are shown. The peak efficiency points correspond to the baseline case, as they did in the pressurized system. If the baseline TIT is higher than the desired TIT (to the left of the peak) in the larger ΔT_c cases (200 °C), the recuperator effectiveness should be decreased, resulting in efficiency reduction. The additional fuel supply to meet the desired TIT reduces the efficiency, as usual. Therefore, the peak efficiency is always lower than that of the pressurized system. The smaller ΔT_c cases (100 °C) always require the additional fuel supply due to the very low TIT of the baseline case, as explained in Section 4.1. Around 800–950 °C, which is the most probable TIT of commercial gas turbines at this low pressure ratio, the gas turbine power fraction in the case of ΔT_c 100 °C is larger than that of the pressurized system. However, efficiency

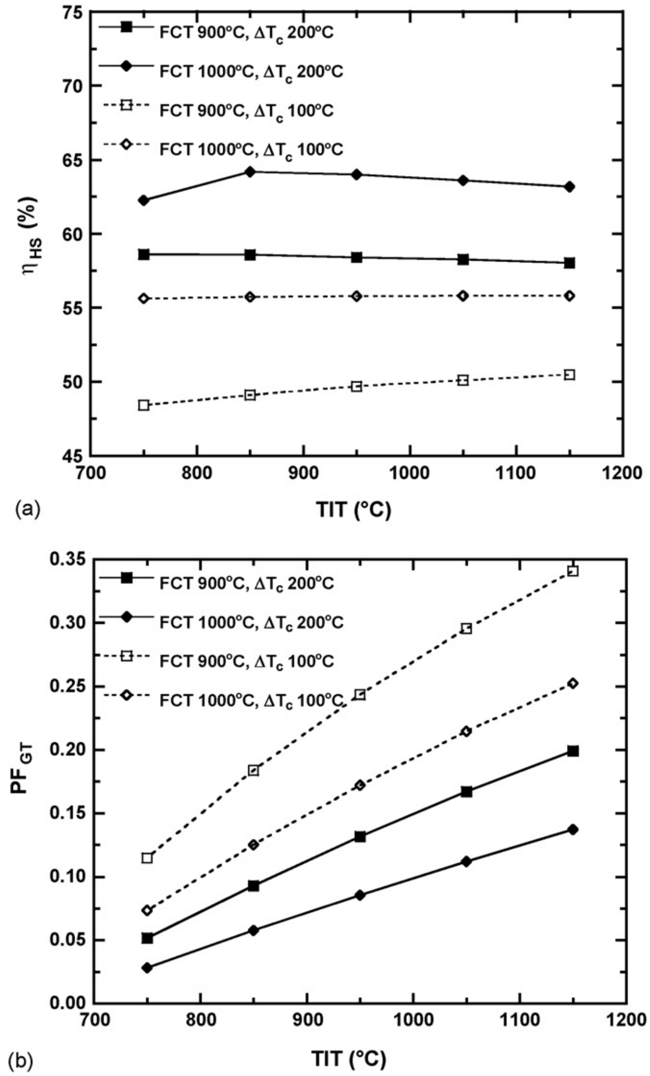

Fig. 10. Performance of the ambient pressure hybrid system for different combinations of the fuel cell temperature and the turbine inlet temperature (pressure ratio of 8.5): (a) system efficiency and (b) gas turbine power fraction.

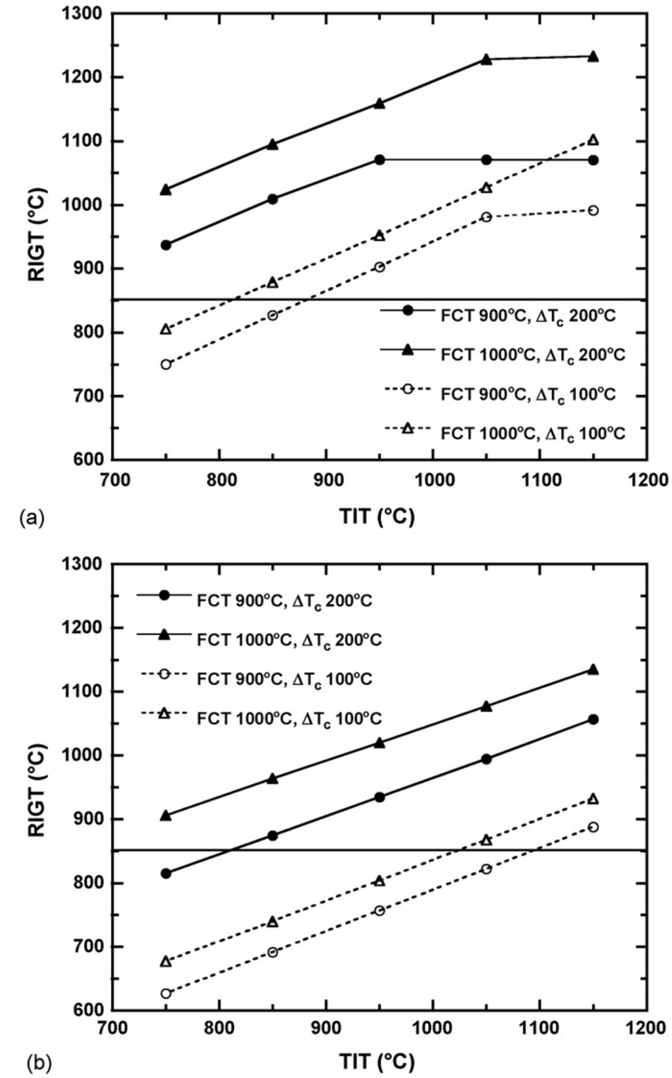

Fig. 11. Recuperator inlet gas temperature of the ambient pressure hybrid system: (a) pressure ratio of 3.5 and (b) pressure ratio of 8.5.

of this range hardly exceeds the efficiency of the SOFC only system. The region of the additional fuel supply usually requires the air bypass to obtain the desired cathode inlet temperature. Thus, for a fixed SOFC power, the air flow rate through the gas turbine decreases, so the gas turbine power fraction reduces.

Fig. 10 shows the results for the pressure ratio of 8.5. Here, all design conditions require the additional fuel supply. Similar to the results of the pressurized system of the same pressure ratio (Fig. 8), the efficiency reduces only moderately with TIT increase. Furthermore, in the cases with a smaller ΔT_c (100 °C), the efficiency remains almost constant or even enhances as the TIT increases. However, the efficiencies of this smaller ΔT_c cases are lower than those of the SOFC only system by 3–4%. In the high TIT region, the gas turbine power fraction is higher than that of the pressurized system.

The recuperator temperature is another important design parameter and should be checked. In the pressurized system, the recuperator inlet gas temperature remains sufficiently below 600 °C, so the recuperator can be manufactured with steel without any problems. In the ambient pressure system, the recuperator inlet gas temperature may be very high because the exit gas from the SOFC module flows into the recuperator. A similar problem occurs in the ambient hybrid system using the molten carbonate fuel cell [12], where the recuperator inlet gas temperature is expected to range between 600 and 800 °C and high temperature alloys are required to accommodate the temperature. Fig. 11 shows the recuperator inlet temperature of the present ambient SOFC hybrid system for the two pressure ratios. The temperature is higher than 600 °C for all conditions. Of course, a higher pressure ratio results in a relatively lower recuperator temperature. But this temperature is still sufficiently high. Therefore, super alloys should be used to manufacture the recuperator. Allowable temperature depends on lifetime, but the usual limit of state-of-the-art alloys is slightly higher than 800 °C. In a recent study [9], 825 °C was suggested as the guideline. A slightly more challenging example of 850 °C is indicated in figure. With this guideline on the recuperator temperature limit, the practical design range reduces considerably. Only the combinations of the three major parameters that make the recuperator inlet temperature lower than the limit are practically possible design conditions. With the pressure ratio of 3.5, all cases based on the SOFC with a larger ΔT_c (200 °C) can hardly be realized because the recuperator temperature is excessively high. The possible design region with the ΔT_c of 100 °C is also confined to a very limited range of the TIT of less than 900 °C. But, in this region, the hybrid system efficiency is not improved significantly from that of the SOFC only system, as we have examined. At the pressure ratio of 8.5, most of the large ΔT_c cases are not feasible to design. The available TIT range of smaller ΔT_c cases is rather wide. However, as seen from Fig. 10(a), the system efficiency in that region (high pressure ratios with a small temperature difference at the cell) is lower than that of the SOFC only system. In conclusion, the ambient pressure SOFC hybrid system is not quite feasible, especially when a gas turbine with high pressure ratio is used, because the relatively high efficiency conditions are excluded from the available design range considering the practical temperature limitation of the recuperator and moreover, the remaining acceptable conditions provide only marginal efficiency gain over the SOFC only system or even a loss of the efficiency.

5. Conclusions

This study investigated the design of both pressurized and ambient pressure SOFC/GT hybrid systems and compared their performance characteristics for various design environments. The following can be summarized.

In the baseline hybrid layouts, the turbine inlet temperature decreases with increasing the pressure ratio, but this trend does not accord with the current design practice of gas turbines. The pressurized system exhibits higher efficiencies than the ambient pressure system for all design conditions. The ambient pressure system is not feasible when a high pressure ratio gas turbine is used because the required turbine inlet temperature is too low.

To overcome the mismatch between the characteristics of the baseline hybrid system and the gas turbine design practice, the additional fuel supply as well as the air bypass can be utilized. As the additional fuel supply increases, the turbine inlet temperature and the gas turbine power fraction increase but the efficiency generally drops. A higher pressure ratio requires more additional fuel supply to obtain the same turbine inlet temperature. A lower fuel cell temperature and a smaller temperature difference at the cell also require more additional fuel supply. The efficiency of the system with a higher pressure ratio is less sensitive to the turbine inlet temperature than that of the system with a lower pressure ratio.

Increasing the pressure ratio of the gas turbine hardly improves the system efficiency, but the increase of the power share of the gas turbine is advantageous in terms of the unit cost of the hybrid system. Considering the practical limitation on the recuperator temperature, the possible design range of the ambient pressure system becomes limited. Decreasing the temperature difference at the cell relaxes the recuperator temperature problem. However, the ambient pressure system with high pressure ratio is still not quite feasible because the efficiency of the available design conditions is generally lower than that of the SOFC only system.

Acknowledgments

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