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Influence of steam injection through exhaust heat recovery on the design performance of solid oxide fuel cell – gas turbine hybrid systems †

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Abstract

This study analyzed the influence of steam injection on the performance of hybrid systems combining a solid oxide fuel cell and a gas turbine. Two different configurations (pressurized system and ambient pressure system) were examined and the effects of injecting steam, generated by recovering heat from the exhaust gas, on system performances were compared. Performance variations according to the design of different turbine inlet temperatures were examined. Two representative gas turbine pressure ratios were used. Without steam injection, the pressurized system generally exhibits higher system efficiency than the ambient pressure system. The steam injection augments gas turbine power, thus increasing the power capacity of the hybrid system. The power boost effect due to the steam injection is generally greater in the relatively higher pressure ratio design in both the pressurized and ambient pressure systems. The effect of the steam injection on system efficiency varies depending on system configurations and design conditions. The pressurized system hardly takes advantage of the steam injection in terms of system efficiency. On the other hand, the steam injection contributes to the efficiency improvement of the ambient pressure system in some design conditions. In particular, a higher pressure ratio provides a better chance of efficiency increase due to the steam injection.

Keywords: Solid oxide fuel cell; Gas turbine; Hybrid; Pressurized system; Ambient pressure system; Steam injection

1. Introduction

As the potential of the solid oxide fuel cell (SOFC) for an electric power source has become more evident, the need for its performance upgrade has increased. Hybridization of the SOFC with another power generation device such as a gas turbine (GT) is one of those efforts. Attempts are being made to advance SOFC system design and upgrade its performance through hybridization [1]. In addition to the increase of cell performance, the increase of GT performance and optimized combinations of SOFC and GT plays an important role in enhancing the hybrid system performance. With regard to the system integration, the most fundamental design factor is the operating pressure of the fuel cell. Fuel cells can be designed to operate either at an ambient pressure (ambient pressure system) or at an elevated pressure (pressurized system). Until now, more design efforts have been given to the pressurized system [2,3]. However, the need for developing ambient pressure hybrid SOFC systems has also been recognized [4]. Since there exist various ways in combining an SOFC and a GT and design principles of the two devices are quite different, research has been carried out regarding optimal matching of the two sub-systems [5,6,7]. In previous studies [8,9], both the pressurized system and the ambient pressure system were analyzed on a consistent basis and their performance characteristics were critically

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compared. Analyses were performed for a wide range of design parameters such as the cell temperature and the turbine inlet temperature. A summary of those studies is that the pressurized system generally exhibits a higher system thermal efficiency for equivalent design conditions. The pressurized system may have less exhaust exergy loss, which explains the efficiency superiority [9].

Upgrading the gas turbine performance may also contribute to the enhancement of the hybrid system performance. Injecting steam into the high pressure side (usually to the combustor) has been acknowledged as an effective means of improving both power and efficiency of the gas turbine [10,11]. Steam is usually generated by recovering waste heat from the GT exhaust because the temperature of the GT exhaust gas is sufficiently high. Therefore, the steam injection may have favorable influence on the performance of the hybrid system as well. A previous study [12] examined the possibility of the steam injection on the pressurized system performance and concluded that steam injection gives either favorable or unfavorable effect on the system efficiency depending on the operating condition. A possibility of performance enhancement by steam injection in the ambient pressure hybrid system based on a molten carbonate fuel cell has also been reported [13].

This work analyzes the influence of steam injection on design performance of both the pressurized and ambient pressure SOFC/GT hybrid systems. For this purpose, reference hybrid system configurations were revised to include the heat recovery and the steam injection processes. For a feasible comparison, consistent operating parameters of the fuel cell were adopted. The effects of the steam injection on the system performance were compared between the two different hybrid systems.

2. System configuration

Fig. 1 shows the two different hybrid system configurations analyzed in this study. The fuel cell module, which includes a cell stack, a steam internal reformer, an afterburner and a preheater, is common in the two systems. The major difference is in the operating pressure of the fuel cell. 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 preheater heats up

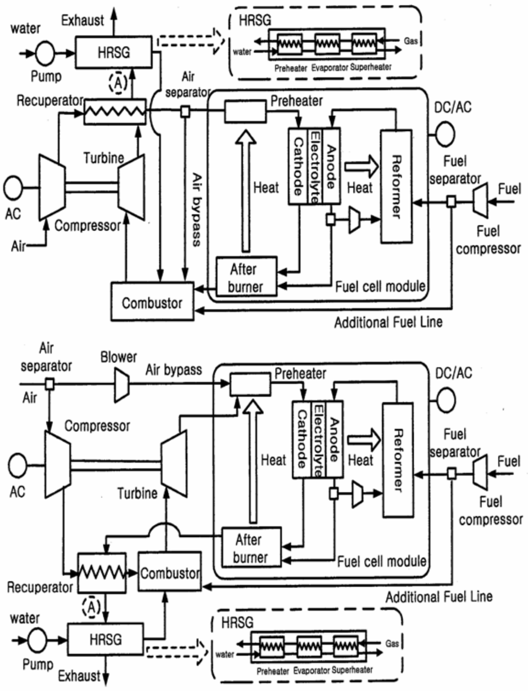

Fig. 1. SOFC/GT hybrid system with heat recovery and steam injection: pressurized system (top) and ambient pressure system (bottom).

the incoming air to meet the required cathode inlet temperature. In the pressurized system, the pressurized air from the compressor enters the SOFC first, and then the SOFC exit gas drives the turbine. On the other hand, in the ambient pressure system, the compressed air drives the turbine first, and thus the SOFC operates at a pressure close to the atmospheric pressure, driven by the turbine exit gas. The purpose of the additional fuel supply line and the air bypass line is to assign arbitrary turbine inlet temperature (TIT). By modulating the amounts of the additional fuel supply and the air bypass, various combinations of the fuel cell temperature and the turbine inlet temperature are possible and their effect on the hybrid system performance can be investigated. A more detailed description of these functions can be found in previous works [5,8,9]. Except the heat recovery steam generator and the subsequent injection of steam to the combustor, the configurations are identical to the ones analyzed in the previous study [8,9], and are called 'base systems' in this work. The specific feature adopted in this study is the generation of steam in the heat recovery steam generator (HRSG) by using the heat of the exhaust gas and its injection into the combustor prior to the turbine.

3. Modeling and analysis

Each component is modeled as a lumped control volume. Complicated models such as multi-dimensional models are more suitable to analyses intended to predict property variations inside the component, especially the cell stack. Since this study aims to analyze the performance of complex systems consisting of many components and furthermore detailed component geometries are not considered, lumped control volume models are sufficient. For example, the cell model is quite feasible for system analysis as long as a reasonable cell voltage is adopted and a full energy balance is used.

The methane, supplied to the system, is reformed to a hydrogen-rich fuel in the reformer. The following steam reforming is adopted.

$$\text{Steam reforming}: \ CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (1)$$

$$\text{Water gas shift}: \ CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2)$$

Equilibrium reactions are assumed and heat required for this endothermic reactions comes from the cell stack. The steam carbon ratio, defined as follows, determines the amount of steam supplied to the reformer. Since the steam is supplied by the anode gas recirculation, this ratio determines the recirculation flow rate.

$$SCR = \frac{\dot{n}_{H_2O}}{\dot{n}_{CH_4}} \quad (3)$$

Among the five components (H_2, CO, CH_4, CO_2, H_2O), hydrogen and carbon monoxide participate in the following electrochemical reactions at the fuel cell, producing direct current. Also, water steam is produced at the anode.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O, \ \ CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (4)$$

Prior to these electrochemical reactions, a steam reforming reaction inside the cell, similar to Eqs (1) and (2), is also considered because the cell operating temperature is sufficiently high.

The amount of reacted cell fuel is calculated by using the following definition of fuel utilization factor at the cell. Thus, redundant H_2 and CO as well as remaining CH_4, CO_2 and H_2O exit the cell.

$$U_f = \frac{(\dot{n}_{H_2} + \dot{n}_{CO})_{reacted}}{(\dot{n}_{H_2} + \dot{n}_{CO})_{supplied}} \quad (5)$$

Since this study is a system design mode calculation, it is assumed that the current density of the unit cell is designed to be constant for all cases. Therefore, different powers obtained from the analysis can be realized by different cell stack sizes (e.g. number of stacked cells). However, the dependence of the cell voltage on operating temperature and pressure is considered on the basis of published correlations. The cell voltage is predicted by subtracting various losses (activation polarization and ohmic losses) from the Nernst potential as follows.

$$V = E_N - E_P - (E_a + E_e + E_c) \quad (6)$$

The Nernst potential is calculated from the theoretical Gibbs function difference for the electro-chemical reaction as usual. The activation polarization loss and the ohmic losses at the anode, cathode and electrolyte are predicted by correlations available in the literature [14, 15]. A constant current density ($400 mA/cm^2$) is given to all design conditions.

Based on the cell voltage, the DC power of the SOFC stack is calculated as follows, where electric current is calculated from the molar flow rates of reacted hydrogen and carbon monoxide and the Faraday constant.

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

At the cell, a full energy balance including the heat release to the internal reformer is modeled. The AC power of the SOFC is calculated as follows considering DC-AC conversion efficiency and auxiliary power such as recirculation blower power.

$$\dot{W}_{FC,AC} = \dot{W}_{FC,DC} \cdot \eta_{conv} - \dot{W}_{AUX} \quad (8)$$

In the gas turbine side, injection of the steam, generated at the HRSG, to the combustor is modeled. The HRSG is segmented into three modules: a preheater, an evaporator, and a superheater. Each module is modeled as a counter flow heat exchanger and an energy balance between the hot fluid (gas) and the cold fluid (water or steam) is applied as follows.

Table 1. Component design parameters.

Fuel Cell	
Cell temperature	900°C
Cell voltage (1.0, 3.5, 8.5 bar)	0.731, 0.758, 0.781 V
Steam to carbon ratio	3.0
Utilization factor	0.7
DC to AC conversion efficiency	0.93
Gas turbine and others	
Pressure ratio	3.5, 8.5
Turbine inlet temperature	750~1150°C
Compressor efficiency	0.78
Turbine efficiency	0.85
Mechanical efficiency	0.96
Generator efficiency	0.93
Recuperator efficiency	≥ 0.83
HRSH pinch and approach Temperature difference	10°C

$$\dot{m}_g(h_{in} - h_{out})_g = \dot{m}_s(h_{out} - h_{in})_s \tag{9}$$

A proper pinch point temperature difference (gas exit temperature minus saturation temperature of the water at the evaporator) is assigned at the evaporator, and an approach temperature difference (gas inlet temperature minus the steam exit temperature at the superheater) is assigned at the superheater.

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

$$\dot{W}_{GT,AC} = (\dot{W}_T \cdot \eta_m - \dot{W}_C) \cdot \eta_{gen} - \dot{W}_{AUX} \tag{10}$$

The net hybrid system power and the thermal efficiency are calculated as follows.

$$\dot{W}_{SYS} = \dot{W}_{FC,AC} + \dot{W}_{GT,AC} \tag{11}$$

$$\eta_{SYS} = \frac{\dot{W}_{SYS}}{(\dot{m} \cdot LHV)_{CH_4}} \tag{12}$$

Table 1 lists major design parameters used in the analysis. Depending on cell material, the cell operating temperature varies much between 600 and 1000°C among different manufacturers. The cell voltage usually increases as operating temperature increases and a high cell temperature allows a better combination with the high gas turbine temperature. Therefore, a high cell temperature is preferred for a higher system performance. The cell temperatures of currently available SOFC stacks aimed at hybrid systems application range from 850 to 1000°C [2,3,4]. In this study, a representative cell temperature of 900°C is adopted. The temperature difference at the cell is 200°C, that is, the cathode inlet air temperature is 700°C. Two different pressure ratios (PR) are used: one for the current micro gas turbine (3.5), and the other for the medium size gas turbine (8.5). The voltage correlation with assumed design parameters gives reasonable values, ranging from 0.73 to 0.78 V depending on operating pressure. The turbine inlet temperature range (750-1150°C) covers those of micro- to medium-sized gas turbines (tens of kW to order of MW). Process software [16] has been used for the analysis.

By steam injection, the power fraction of the gas turbine increases. When it comes to the power, this study intends to investigate the relative change of power generation capacity due to steam injection. In the calculation, unit inlet air flow is used. However, since the relative power change is important, relative values instead of absolute power values will be shown in the result. The ratio of gas turbine power to the SOFC power is defined as follows.

$$R = \frac{\dot{W}_{GT,AC}}{\dot{W}_{FC,AC}} \tag{13}$$

In addition, to examine the net power upgrade due to the steam injection, the relative increase of the system power for a fixed SOFC power is defined as follows.

$$\alpha = \frac{1 + R_{SI}}{1 + R_{Base}} - 1 \tag{14}$$

where $1+R$ means the total system power per unit SOFC power. Therefore, means the relative power increase due to the steam injection when a fixed SOFC power capacity for both base and steam-injected system is considered, thus representing the net effect of the steam injection in terms of system power.

4. Results and discussion

4.1 Temperature characteristics and steam production capability

It is useful to examine the characteristics of the ex-

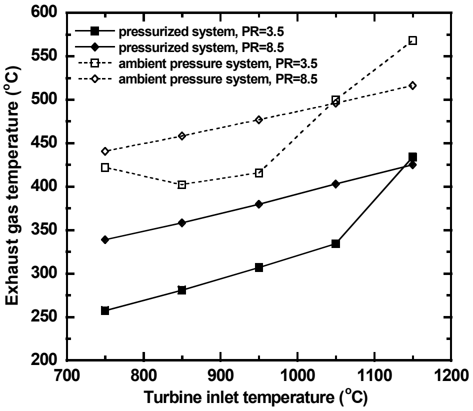

Fig. 2. Exhaust gas temperature of the base systems without steam injection.

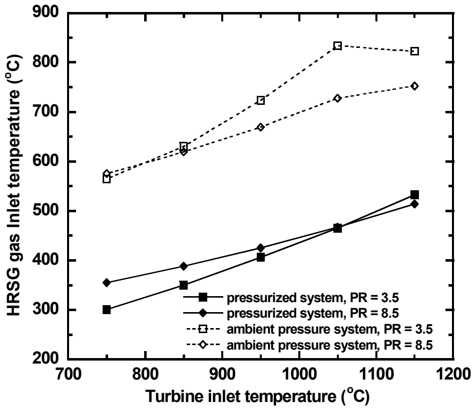

Fig. 3. HRSG gas inlet temperature (location A in Fig. 1) of the steam-injected systems.

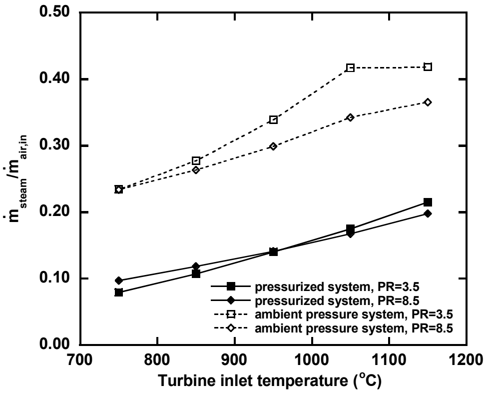

Fig. 4. Ratio of produced steam flow rate to system inlet air flow rate.

haust gas of the base systems without the steam injection prior to examining those of the steam-injected systems. Fig. 2 shows the exhaust gas temperature after the recuperator (location A) in the base systems. The hot gas after the fuel cell directly flows into the recuperator in the ambient pressure system, while the gas expands at the turbine before it flows into the recuperator in the pressurized system. This is the main reason why the exhaust temperature of the ambient pressure system is higher than that of the pressurized system as shown in Fig. 2. The relatively higher exhaust temperature of the ambient system is an indicator of the relatively lower system efficiency because a high exit temperature means a less effective utilization of thermal energy inside the system. However, a higher temperature can be advantageous in terms of heat recovery. As the gas inlet temperature of the HRSG (location A) becomes higher, more heat can be recovered, and thus more steam can be produced. Fig. 3 shows the gas inlet temperature of the HRSG for the steam-injected systems. In general, as the turbine inlet temperature increases, the HRSG inlet gas temperature increases. At the design condition of the ambient pressure system with pressure ratio of 3.5 and TIT of 1150°C, the slope of the temperature variation changes. At this point, the main combustor consumes much oxygen due to the relatively high TIT, and the oxygen is further consumed for the electrochemical reaction at the cell. Then, there does not exist sufficient oxygen at the afterburner to completely burn the redundant fuel from the cell. Consequently, the temperature of the gas after the afterburner, and thus the temperature after the recuperator do not reach the value extrapolated from the slope. On the contrary, it is moderately reduced.

The HRSG inlet gas temperature is higher in the ambient pressure system than in the pressurized system. In general, for a given turbine inlet temperature, the recuperator exit temperature is higher in the steam-injected systems compared to the base systems because the increased hot gas mass flow at the recuperator due to injected steam results in a lower gas temperature drop at the recuperator. Fig. 4 shows the ratio between the produced steam flow rate to the system inlet air flow rate. As a result of the relatively higher HRSG inlet gas temperature, the steam generation of the ambient pressure system is much greater in comparison to the pressurized system.

4.2 Performance of the pressurized system

Fig. 5 presents results of the pressurized system with a pressure ratio of 3.5. Variations in the power ratio (R), the relative increase of power (α) and the

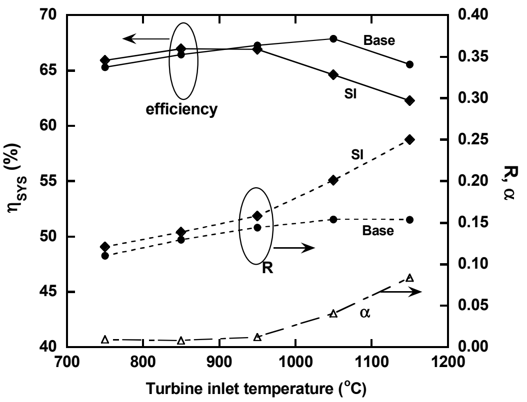

Fig. 5. Influence of steam injection on the performance of the pressurized system with pressure ratio of 3.5.

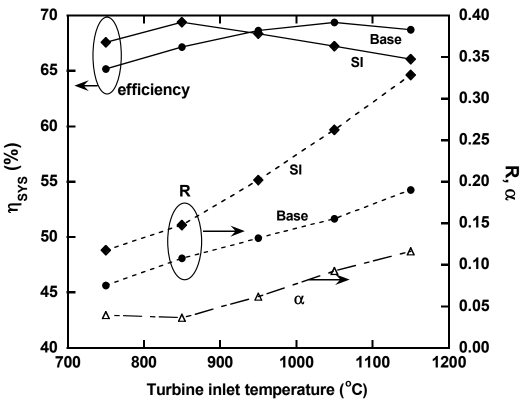

Fig. 6. Influence of steam injection on the performance of the pressurized system with pressure ratio of 8.5.

system efficiency are shown. In the base system, the power ratio (R) increases moderately with increasing TIT. Due to the turbine power augmentation by the increased turbine mass flow, the steam injection increases the GT power share. As TIT gets higher, the power boost effect due to the steam injection becomes greater. At TITs over 1050°C, the GT power becomes more than 20% of the SOFC power. The relative power enhancement (α) is small and nearly uniform in the low TIT range, while it increases with TIT in the higher TIT range. If TIT reaches 1100°C, more than a 5 percent system power increase is possible for a given SOFC power capacity.

The efficiency peaks at a certain TIT, corresponding to a condition where no additional fuel and air bypass are used. To the left of the peak point, the fraction of the air bypassed to the turbine side increases and system efficiency lessens as TIT decreases. After the peak point, additional fuel supply to the combustor is required to meet the high TIT. Increasing the additional fuel supply decreases the system efficiency. In the steam-injected system, the trend of efficiency variation with TIT is similar to that of the base system. However, the hot gas can heat the fuel cell inlet air to the required cell inlet temperature with a relatively lower TIT in comparison to the base system because the hot gas flow rate relative to the flow rate of the air to be heated at the recuperator is greater due to the injected steam. Therefore, the steam injection shifts the peak efficiency point to a lower TIT. The steam injection enhances efficiency slightly in the low TIT range, but lowers efficiency in the high TIT range.

The results of the pressurized system with a pressure ratio of 8.5 are shown in Fig. 6. Trends are similar to those of the lower pressure ratio case. The steam-injected system exhibits a greater GT power share for all TITs, thus contributing to the increase of system power for a given SOFC power. The relative system power augmentation increases with increasing TIT as in the previous case, but the power boost effect is even greater. Also, by the steam injection, the peak efficiency point moves to a lower TIT (from about 1050°C to about 850°C) as in the previous case. Around and below the peak efficiency point TIT, the steam-injected system shows a higher efficiency than the base system. The peak efficiency is comparable between the base system and the steam injected system. In general, the effect of the steam injection on the pressurized system can be summarized as follows. In the low TIT regime, the power boost effect is moderate but efficiency can be improved, while in the high TIT regime, a considerable power boost effect is possible with a sacrifice of efficiency.

4.3 Performance of the ambient pressure system

Fig. 7 shows the results for the ambient systems with a pressure ratio of 3.5. In the ambient pressure system, matching between the SOFC and the GT in terms of the fuel cell temperature and the turbine inlet temperature is less favorable than in a pressurized system. When there is no additional fuel supply (peak efficiency point), the turbine inlet temperature is much lower in the ambient pressure system [8]. Therefore, in Fig. 7, the TIT at the peak efficiency point is lower than that of the pressurized system. The additional fuel supply increases as TIT increases. In order to maintain the same cell inlet temperature, the portion of the air directly bypassed to the fuel cell should also be in-

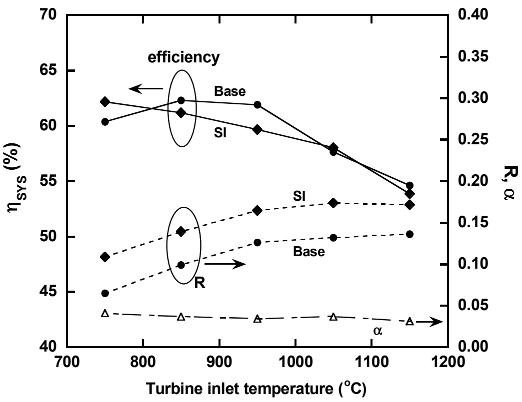

Fig. 7. Influence of steam injection on the performance of the ambient pressure system with pressure ratio of 3.5.

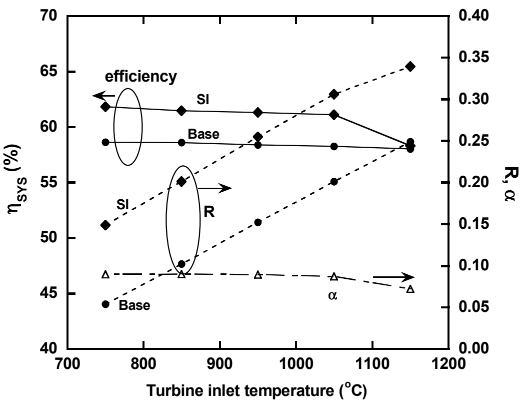

Fig. 8. Influence of steam injection on the performance of the ambient pressure system with pressure ratio of 8.5.

creased as TIT increases. As in the pressurized system, the steam injection increases the GT power share, thereby contributing to the system power upgrade. However, the increased mass flow at the turbine tends to increase the SOFC power as well because the turbine exit flow directs to the SOFC. Thus, as TIT gets higher, the power ratio curves do not diverge as much as the curves do in the pressurized system. As a result, the relative power augmentation (α) remains nearly constant. The efficiency of the ambient pressure system is lower than the pressurized system for all design conditions (compare the base system efficiencies in Figs. 5 and 7). As in the pressurized system, the peak efficiency point moves to a lower TIT point. The peak efficiency point of the steam-injected system lies outside the lowest TIT range considered. Efficiency enhancement due to the steam injection is possible only when the turbine inlet temperature is sufficiently low.

Results for the higher pressure ratio (8.5) cases are shown in Fig. 8. The power boost effect due to the steam injection is more evident than in the low pressure ratio case. Again, the relative power increase (α) is nearly constant, but is much greater than in the lower pressure ratio case. In the base system, the peak efficiency point is around the TIT region that is furthest left (~750°C). Increasing the additional fuel decreases system efficiency, but the variation is quite moderate. The steam injection pushes the peak efficiency point to an even lower TIT (outside the current TIT range). In this case, the steam injection provides a sensible efficiency upgrade for a wide TIT range.

To compare the influence of the steam injection on both the pressurized and ambient pressure systems, let's consider, as an example, any TIT condition where an additional fuel supply is required. In the pressurized system, in order to obtain a given TIT, the steam injection to the combustor increases the additional fuel supply. However, this hardly affects the power output and fuel supply to the SOFC. Consequently, even though the system power increases by the steam injection at a given TIT, the system efficiency does not increase but usually decreases because the fuel supply to the less efficient sub-system (GT) is increased. Results of Figs. 5 and 6 demonstrate this phenomenon. In the ambient pressure system, the increased steam composition in the turbine gives rise to an increase of turbine exit temperature. Thus, the heat transfer from the combustor to the preheater in order to heat up the turbine exit gas decreases. This increases the recuperator inlet gas temperature, resulting in an increased combustor inlet air temperature. Consequently, even though the mass flow rate in the combustor increases due to the steam injection, the additional fuel supply to meet a given TIT can be minimized. As a result, in the ambient pressure system, the increment in the fuel supply is usually comparable to or less than the increment of power. Accordingly, efficiency improvement is possible as shown in the high pressure ratio case of Fig. 8. Among four cases considered in this study, the ambient pressure system with a high pressure ratio shows the most favorable effect of the steam injection in terms of system efficiency upgrade. About a 3 % increase of efficiency is predicted.

5. Conclusions

This study investigated the influence of steam injection through exhaust heat recovery on the performance of both pressurized and ambient pressure SOFC/GT hybrid systems. The results are summarized as follows.

(1) The exhaust gas temperature in the base hybrid systems is high enough to produce a sensible amount of steam by heat recovery. The relatively higher exhaust temperature of the ambient pressure systems provides greater steam production in comparison to the pressurized system.

(2) The steam injection augments the gas turbine power, thus increasing the power capacity of the hybrid system. The relative power augmentation generally increases with increasing turbine inlet temperature in the pressurized system, while it remains almost constant in the ambient pressure system. The power boost effect due to the steam injection is generally greater in the relatively higher pressure ratio design in both the pressurized and ambient pressure systems.

(3) The turbine inlet temperature at the peak point becomes lower by the steam injection. In the pressurized system, the steam injection hardly improves the peak system efficiency, while in the ambient pressure system the steam injection provides a considerable efficiency improvement for a relatively high pressure ratio design.

(4) Even in design conditions where an efficiency upgrade is not very evident, the reduction of development cost due to an increase of the power portion of the gas turbine, which is less expensive per unit power size, can be another advantage. However, there also exists a technical barrier to overcome. As the steam content increases, the thermal load of hot sections such as in a turbine increases. Also, erosion and corrosion problems may be accelerated. Considering all these factors, an upgraded design of hot sections of the gas turbine would be required.

Acknowledgment

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Nomenclature

E	:	Electric potential (V)
F	:	Faraday constant [96,486 C/mol]
GT	:	Gas turbine
HRSG	:	Heat recovery steam generator
h	:	Specific enthalpy [kJ/kg]
LHV	:	Lower heating value [kJ/kg]
$\dot{m}$	:	Mass flow rate [kg/s]
$\dot{n}$	:	Molar flow rate [kmol/s]
PR	:	Pressure ratio of the gas turbine
R	:	Power ratio
SCR	:	Steam carbon ratio
SOFC	:	Solid oxide fuel cell
TIT	:	Turbine inlet temperature [^{o}C]
U_f	:	Fuel utilization factor at the cell
V	:	Voltage [V]
$\dot{W}$	:	Power [kW]
α	:	Relative power increase
η	:	Efficiency

Subscript

a	:	Anode
AC	:	Alternating current
AUX	:	Auxiliary
Base	:	Systems without steam injection
C	:	Compressor
c	:	Cathode
conv	:	Conversion
DC	:	Direct current
e	:	Electrolyte
FC	:	Fuel cell
g	:	Gas
gen	:	Generator
GT	:	Gas turbine
in	:	Inlet
m	:	Mechanical
out	:	Outlet
P	:	Polarization
s	:	Steam
SI	:	System with steam injection
sys	:	System
T	:	Turbine

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