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Cycle analysis of an integrated solid oxide fuel cell and recuperative gas turbine with an air reheating system

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Abstract

Cycle simulation and analysis for two kinds of SOFC/GT hybrid systems were conducted with the help of the simulation tool: Aspen Custom Modeler. Two cycle schemes of recuperative heat exchanger (RHE) and exhaust gas recirculated (EGR) were described according to the air reheating method. The system performance with operating pressure, turbine inlet temperature and fuel cell load were studied based on the simulation results. Then the effects of oxygen utilization, fuel utilization, operating temperature and efficiencies of the gas turbine components on the system performance of the RHE cycle and the EGR cycle were discussed in detail. Simulation results indicated that the system optimum efficiency for the EGR air reheating cycle scheme was higher than that of the RHE cycle system. A higher pressure ratio would be available for the EGR cycle system in comparison with the RHE cycle. It was found that increasing fuel utilization or oxygen utilization would decrease fuel cell efficiency but improve the system efficiency for both of the RHE and EGR cycles. The efficiency of the RHE cycle hybrid system decreased as the fuel cell air inlet temperature increased. However, the system efficiency of EGR cycle increased with fuel cell air inlet temperature. The effect of turbine efficiency on the system efficiency was more obvious than the effect of the compressor and recuperator efficiencies among the gas turbine components. It was also indicated that improving the gas turbine component efficiencies for the RHE cycle increased system efficiency higher than that for the EGR cycle.

Keywords: Solid oxide fuel cell; Cycle analysis; Recuperative heat exchanger; Exhaust gas recirculation

1. Introduction

The hybrid system of solid oxide fuel cell (SOFC) combined with gas turbine (GT) cycle has been identified to be a superior power-generation technology compared to many other options. A cycle scheme is believed to be one of the important technologies in system design or optimization. This was verified with many operating parameters of the system, such as SOFC operating temperature and pressure. Hence, cycle analysis forms the basis of a cycle design for a hybrid system. Some examples of hybrid cycle performance analysis can be found in Refs. [1–6]. In the majority of these papers, a parametric study focused on the recuperated SOFC/GT cycle. Rao and Samuelsen [3] presented an analysis of the hybrid cycle originally proposed by Westinghouse (SureCell^{TM}). Chan et al. [5] studied a hybrid system based on an internal-reforming SOFC stack with particular attention to the effects of operating pressure and fuel flow-rate on the performance of components and overall system. In particular, Williams et al. [6] investigated pressurized and unpressurized hybrid systems based on a planar medium temperature SOFC, which indicated that the system efficiency was raised by the recirculation of a proportion of the fuel cell exhaust gas to heat the inlet air.

The aim of the present work is to analyze an integrated SOFC and recuperative GT hybrid system that is combined with an air reheating cycle. Attention is devoted to the analysis of two cycle schemes for air reheating, one named the indirect method uses a recuperative heat exchanger (RHE) while the other named the direct method utilizes the SOFC exhaust gas recirculation

Abbreviations: AM, air manifold; BoP, balance of plant; BS, booster; CP, compressor; CB, combustor; EGR, exhaust gas recirculation; GM, gas manifold; GT, gas turbine; HE, heat exchanger; HS, heat stream; HUM, humidifier; MIX, mixer; PH, pre-heater; PR, pre-reformer; RHE, recuperative heat exchanger; SG, steam generator; SOFC, solid oxide fuel cell; SPL, splitter; SS, stream state; TB, turbine; TIT, turbine inlet temperature; WS, water stream

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Nomenclature

A	area (m^2)
A_{nozz}	flow area of nozzle (m^2)
C_p	specific heat capacity at constant pressure ($J\,kg^{-1}\,K$)
i	current density ($A\,m^{-2}$)
$\dot{m}$	mass flow ($kg\,s^{-1}$)
$\dot{n}$	molar flow ($mol\,s^{-1}$)
p	operating pressure (Pa)
q	chemical reaction heat ($J\,mol^{-1}$)
R_g	mass universal gas constant ($J\,kg\,K^{-1}$)
T	temperature (K)
U	voltage (V)
U_a	fuel cell air utilization
U_f	fuel cell fuel utilization
w_{spec}	specific output power (power per unit airflow $kW\,kg^{-1}$)
W	power (kW)
x	gaseous molar fraction

Greek letters

ε	heat exchanger effectiveness
η	efficiency
ρ	density ($kg\,m^{-3}$)

Subscripts

active	chemical active
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
H_2O	water (gas)
N_2	nitrogen
O_2	oxygen
SYS	system
tot	total

Superscripts

anode	anode side control volume
cathode	cathode side control volume
in	inlet
oput	output

(EGR). First, we put forward the RHE and EGR cycle schemes of a hybrid SOFC/GT system, respectively, in Section 2. Then in Section 3 steady simulations for two cycles of RHE and EGR scheme are implemented with the help of the simulation tool Aspen Custom Modeler [7]. The characteristics of the cycles are identified according to the simulation results. Moreover, the system performances are presented and analyzed for both cycle schemes. Based on these, we discuss the effects of some parameters on the system efficiency, for example the oxygen utilization, fuel utilization, operating temperature, and gas turbine components performance.

2. Cycle flowsheets

Fig. 1 shows the flowsheet of the SOFC/GT hybrid system combined with an RHE cycle. The air from the vessel AM is first compressed in a compressor CP2 and then preheated by the exhaust flow from the turbine in a recuperator HE2. Afterwards, the pre-heated air is reheated in a high-temperature recuperative heat exchanger HE3. The air outlet temperature of HE3 is controlled by adjusting the mass flow of the stream SS17 in order to fulfill the requirement of the SOFC inlet temperature. For the fuel stream, the natural gas pressure is firstly raised in the fuel compressor CP1. The higher pressure fuel is pre-heated in a low-temperature heat exchanger HE1 and then is humidified in a humidifier HUM. The needed water is generated in a steam generator SG where the exhaust heat from HE1 is again utilized to heat the water from the pump. The fuel stream is then mixed with the recirculation stream that comes from the anode side of SOFC. Part of the methane is reformed in the pre-reformer PR and the residual methane is reformed in the SOFC. The fuel stream from PR needs to be pre-heated to the required temperature of SOFC. This process is completed in PH and the heat is provided by internal heat exchange within the cell. The chemical energy is converted to the electrical energy through the electrochemical reaction taking place in the SOFC. Part of the anode side exhaust gas is recirculated to PR through a recirculation booster BS1 for the pre-reforming requirement and the residual gas is mixed with the cathode side exhaust gas in a mixer MIX1. After the mixer, the mixture gas temperature is raised while the stream passes through a combustor CB, where the residual hydrogen in the gaseous mixture and the methane from the fuel vessel GM2 are burned. Part of the high-temperature gas flows to the recuperative heat exchanger to reheat the air. Two gas streams SS10, SS18 flow together and the confluent gas stream then expands in the turbine TB. The turbine exhaust heat is utilized in the recuperator HE1, HE2 and SG to heat the compressor discharge fuel, air and the water from the pump. One example of an SOFC/GT with RHE air reheating cycle was cited by Siemens Westinghouse [8,9]. In the Siemens Westinghouse designed configuration, the SOFC cathode side inlet air is reheated in a plenum by the combustor high-temperature exhaust gas.

Fig. 2 presents the scheme of the SOFC/GT hybrid system combined with an EGR air reheating cycle, in which the inlet air is reheated by the recirculation of the hot combustor exhaust gas to the fuel cell cathode side instead of the air reheating component HE3. The inlet temperature of the cathode side of SOFC is adjusted to satisfy the requirement by controlling the mass flow of gas stream SS16. The booster BS1 and BS2 are used for the recirculation of stream SS2 and SS16, respectively.

In the above two proposed cycles, the fuel utilization of the fuel cell, oxygen utilization, and inlet gas temperature, the pressure ratio of compressor and the turbine inlet temperature (TIT) are set to be controllable variables. The fuel utilization and oxygen utilization of fuel cell are controlled by adjusting the flow area of GM1 and AM obtaining the variant mass flow, respectively. The compressor CP pressure ratio is controlled by

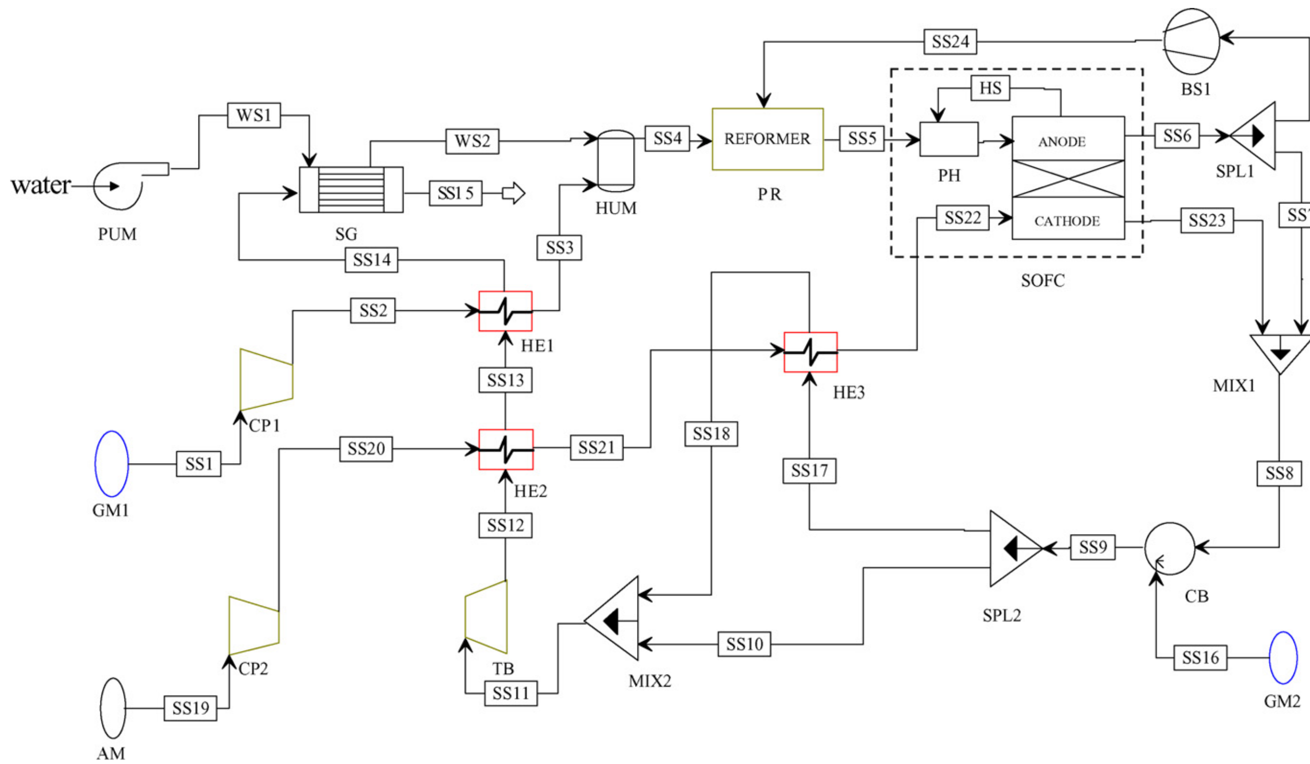

Fig. 1. SOFC/GT combined with RHE air reheating cycle.

regulating the compressor rotation. In the humidifier, steam is added to achieve a certain water-gas ratio for the reforming process. The fuel cell cathode side inlet temperature is controlled by regulating the mass flow of the hot gas that comes from the gas splitter SPL2. In the present study, the geometry of turbine nozzles can be varied and it determines the pressure expansion ratio of the turbine. The turbine inlet temperature is adjusted by changing the mass flux of GM2 fuel flow, which determines the outlet temperature of combustor CB.

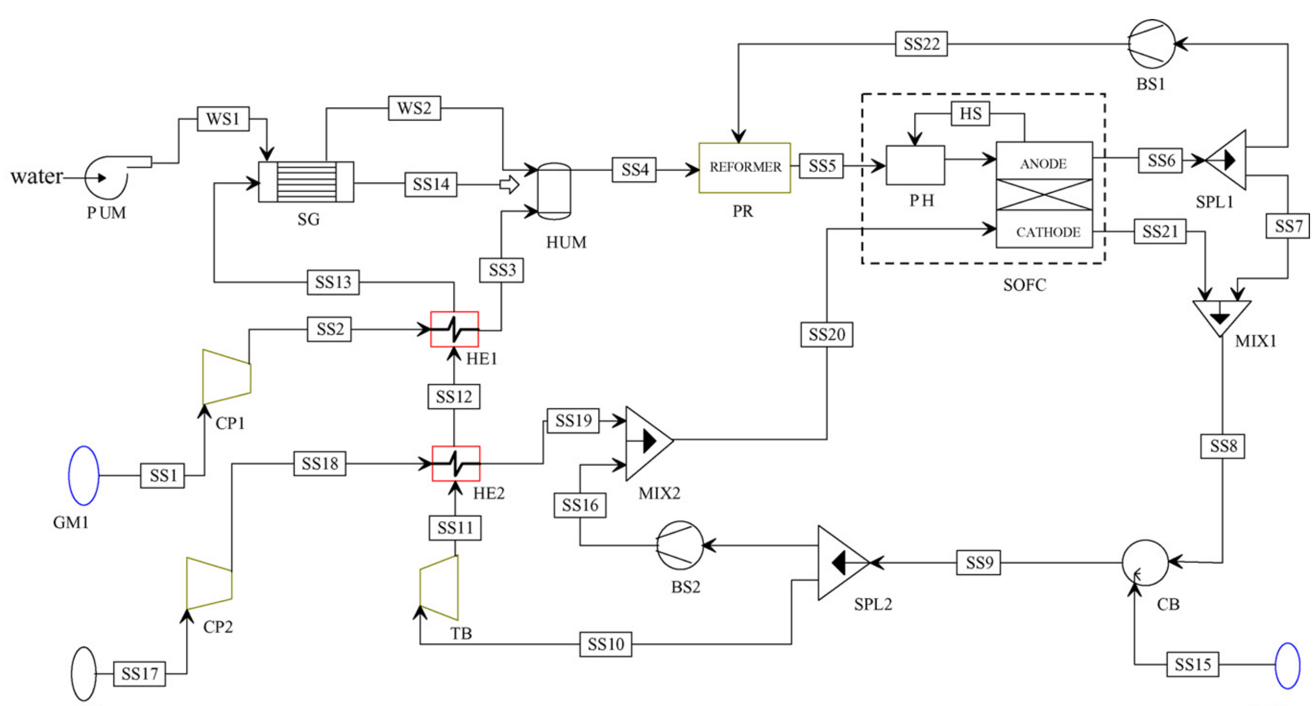

Fig. 2. SOFC/GT combined with EGR air reheating cycle.

3. Simulations and analysis

A planar SOFC presented by International Energy Agency (IEA) [10,11] is employed in the present analysis. The model of the hybrid system used in present simulation is based on the work of reference [12]. Each of the components among the hybrid system was modeled on the basis of the balance equations of mass, energy and force through the whole plant, with specific source terms in different types of components. A one-dimension model was used for the SOFC, which used the Exponential Decay function and the Exponential Associate function to describe the characteristics of the parameters distribution within the SOFC. Here, we define several parameters for the aim of the system analysis. Specific power (power per unit airflow) of system is expressed as:

$$w_{\text{spec}} = \frac{W_{\text{tot}}^{\text{oput}}}{\dot{m}_{\text{CP}}^{\text{air}}} \quad (1)$$

where $W_{\text{tot}}^{\text{oput}}$ denotes the total output power of hybrid system. It is the sum of the SOFC output power and the work done of the turbine, subtracting the power for the compressor and the water pump:

$$W_{\text{tot}}^{\text{oput}} = W_{\text{TB}} + W_{\text{SOFC}}^{\text{oput}} - W_{\text{CP}}^{\text{air}} - W_{\text{CP}}^{\text{fuel}} - W_{\text{PUM}} \quad (2)$$

The fuel cell output power is

$$W_{\text{SOFC}}^{\text{oput}} = UiA_{\text{active}} \quad (3)$$

The SOFC electric generation efficiency is then calculated with

$$\eta_{\text{SOFC}} = \frac{W_{\text{SOFC}}^{\text{oput}}}{U_{\text{f}}(q_{\text{H}_2}\dot{n}_{\text{H}_2}^{\text{in}} + q_{\text{CO}}\dot{n}_{\text{CO}}^{\text{in}} + q_{\text{CH}_4}\dot{n}_{\text{CH}_4}^{\text{in}})} \quad (4)$$

The system efficiency is determined by the total output power and the input energy, and then we get:

$$\eta_{\text{SYS}} = \frac{W_{\text{tot}}^{\text{oput}}}{q_{\text{CH}_4}(\dot{n}_{\text{CH}_4}^{\text{GM1}} + \dot{n}_{\text{CH}_4}^{\text{GM2}})} \quad (5)$$

3.1. Steady state simulation

First the calculation of the steady state is performed using the developed model proposed in Ref. [12] for the RHE and EGR cycles in the Aspen Custom Modeler environment. The parameters of the design point are specified in Table 1. The pressure losses by reason of friction or area change along the flow stream is neglected in the present study.

Table 2 presents the steady simulation results of the RHE cycle scheme. It lists all of the states along the flow stream. From Table 2, it can be observed that the specific heat varies with the temperature and the composition while the gas mass constant is only related with composition. The mass flow of the anode side of the fuel cell, which is represented by the states of SS5, SS6, increases as the flow passes through fuel cell. It is reversed on the cathode side. This is because of the electrochemical reaction which occurred in the SOFC. Based on the results of SS3 and SS4, it can be seen that about 0.0689 kg s^{-1} water vapor is added to the stream due to the need that the methane is reformed in the pre-reformer PR. From the states of SS6 and SS24, we can find about 51% of anode exhaust recirculated to the PR. About 58% of combustor exhaust gases are separated to HE2 to reheat the cathode side air according to the states of SS9 and SS17. SS15 shows the exhaust gas state of the system and the main compositions are nitrogen, water vapor and oxygen.

Table 1
Parameters assumed at design steady point

Compressor	
Isentropic efficiency	85%
Inlet pressure (Pa)	101,325
Inlet temperature (K)	298
Pressure ratio	5.2
Turbine	
Isentropic efficiency	85%
Inlet gas temperature (K)	RHE: 1300, EGR: 1400
Expansion ratio	4.76
SOFC	
Fuel utilization	85%
Oxygen utilization	20%
Current density (A m^{-2})	4000
Inlet temperature (K)	1173
Combustor	
Efficiency	100%
Heat exchanger	
Effectiveness	85%
Pre-reformer	
Steam/methane ratio	2.5
Operating temperature (K)	873
Air manifold	
Composition	O_2: 21%, N_2: 79%
Fuel manifold	
Composition	100% CH_4

Table 3 shows the states of the hybrid system with the EGR air reheating cycle scheme along the gas streams. Compared with that of RHE cycle, large differences can be found in the air mass flow, and the system exhaust composition. For the EGR cycle scheme, the amount of recirculated gas from the splitter SPL is about 119% of fresh air according to the states of SS16 and SS19 in Table 3. Furthermore, the mass flow through the fuel cell cathode is very large for the EGR cycle scheme, which is followed by the fact that the temperature increase through the fuel cell is smaller than that of RHE cycle.

3.2. System performance under variant operating pressure and turbine inlet temperature

System performance is studied by changing the compressor pressure ratio and the turbine inlet temperature. Performance maps are presented in terms of specific power. Fig. 3(a) shows the system performance of the SOFC/GT with an RHE cycle. We found that the optimum pressure ratio was positively correlated with the turbine inlet temperature. The hybrid system peak efficiency at a constant TIT line increased with TIT rising.

Table 2
States of SOFC/GT with RHE cycle

	C_p	$\dot{m}$	x_{CH_4}	x_{CO}	x_{CO_2}	x_{H_2}	x_{H_2O}	x_{N_2}	x_{O_2}	p	R_g	T	ρ
SS1	2191.9	0.0246	1.0000	0	0	0	0	0	0	101325.0	519.4	298.0	0.6547
SS2	2601.5	0.0246	1.0000	0	0	0	0	0	0	526890.0	519.4	402.1	2.5227
SS3	3026.8	0.0246	1.0000	0	0	0	0	0	0	526890.0	519.4	517.5	1.9604
SS4	2225.5	0.0936	0.2857	0	0	0	0.7143	0	0	526890.0	476.8	495.4	2.2305
SS5	2269.8	0.2681	0.0729	0.0138	0.1216	0.1849	0.6068	0	0	526890.0	456.7	873.0	1.3215
SS6	2147.9	0.3490	0	0.0307	0.1512	0.0979	0.7203	0	0	526890.0	402.0	1227.7	1.0675
SS7	2147.9	0.1745	0	0.0307	0.1512	0.0979	0.7203	0	0	526890.0	402.0	1227.7	1.0675
SS8	1280.7	1.8295	0	0.0039	0.0193	0.0125	0.0920	0.7193	0.1530	526890.0	300.3	1227.7	1.4293
SS9	1391.7	1.8496	0	0	0.0418	0	0.1411	0.7116	0.1054	526890.0	300.2	1591.8	1.1025
SS10	1391.7	0.9137	0	0	0.0418	0	0.1411	0.7116	0.1054	526890.0	300.2	1591.8	1.1025
SS11	1330.8	1.8496	0	0	0.0418	0	0.1411	0.7116	0.1054	526890.0	300.2	1300.0	1.3500
SS12	1237.5	1.8496	0	0	0.0418	0	0.1411	0.7116	0.1054	110646.9	300.2	895.1	0.4118
SS13	1172.8	1.8496	0	0	0.0418	0	0.1411	0.7116	0.1054	110646.9	300.2	637.3	0.5783
SS14	1171.5	1.8496	0	0	0.0418	0	0.1411	0.7116	0.1054	110646.9	300.2	632.2	0.5830
SS15	1168.2	1.8496	0	0	0.0418	0	0.1411	0.7116	0.1054	110646.9	300.2	619.3	0.5951
SS16	2191.9	0.0202	1.0000	0	0	0	0	0	0	526890.0	519.4	298.0	3.4043
SS17	1391.7	0.9360	0	0	0.0418	0	0.1411	0.7116	0.1054	526890.0	300.2	1591.8	1.1025
SS18	1261.7	0.9360	0	0	0.0418	0	0.1411	0.7116	0.1054	526890.0	300.2	995.8	1.7624
SS19	1005.1	1.7358	0	0	0	0	0	0.7900	0.2100	101325.0	288.1	298.0	1.1800
SS20	1040.4	1.7358	0	0	0	0	0	0.7900	0.2100	526890.0	288.1	461.1	3.9657
SS21	1105.4	1.7358	0	0	0	0	0	0.7900	0.2100	526890.0	288.1	781.2	2.3407
SS22	1177.0	1.7358	0	0	0	0	0	0.7900	0.2100	526890.0	288.1	1173.0	1.5589
SS23	1189.2	1.6549	0	0	0	0	0	0.8246	0.1754	526890.0	289.5	1227.7	1.4823
SS24	2147.9	0.1744	0	0.0307	0.1512	0.0979	0.7203	0	0	526890.0	402.0	1227.7	1.0675

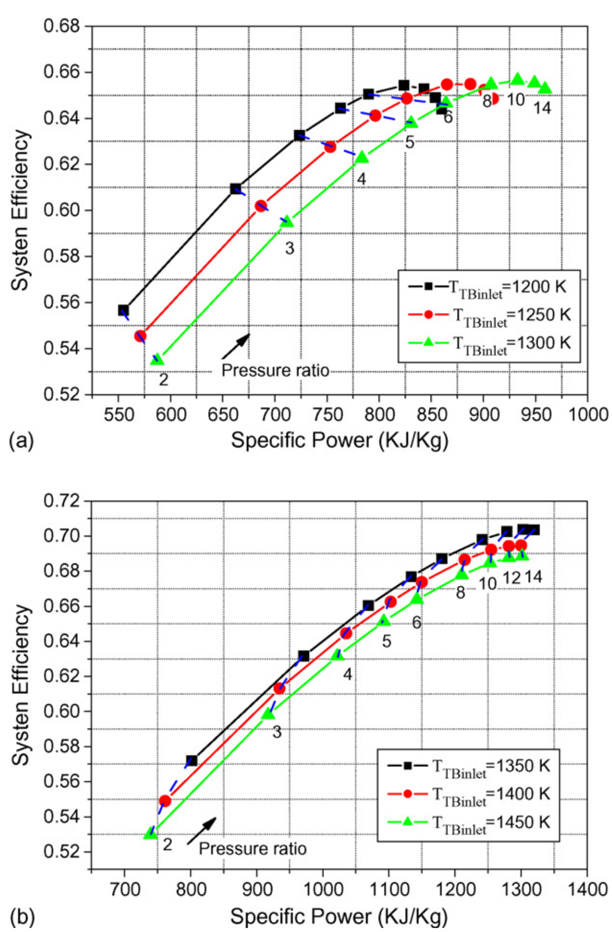

Fig. 3. System performances with variant operating pressure and turbine inlet temperature. (a) RHE cycle and (b) EGR cycle.

System efficiency decreased as TIT rose along the constant line of pressure ratio at the left of peak point. The EGR cycle of hybrid system performance is presented in Fig. 3(b). The peak efficiency is around 70%. Since the flow from the exhaust of the combustor is mixed with the cooling gas from the reheater component HE3 in the RHE cycle, the turbine inlet temperature in the EGR cycle is higher than that in the RHE cycle. Therefore, the optimum pressure ratio for the EGR system is more than 14:1, significantly higher than for the RHE cycle system. Similar to the RHE cycle case, the efficiency of the EGR scheme system is reduced with increase of the turbine inlet temperature. This is because the ratio of output power for GT in the total output power increased with TIT rising. But the gas turbine is less efficient than the fuel cell and this led to a lower overall system efficiency. However, the specific power for the EGR scheme increased as the turbine inlet temperature decreased along the constant pressure ratio line, which differs from the RHE cycle case.

3.3. System performance under variant SOFC load and gas utilization

The fuel cell is the primary component of the hybrid system. The effect of a variable load is firstly studied with variable current density. The assumed parameters are given as shown in Table 1. Fig. 4 shows the efficiency performance in terms of current density. Both SOFC and system efficiencies are negatively correlated with current density. But the SOFC efficiency decreased sooner than that the system efficiency while the current density increased. The system efficiency of the EGR cycle is higher than that of the RHE cycle at this operating condition,

Table 3
States of SOFC/GT with EGR cycle

	C_p	$\dot{m}$	x_{CH_4}	x_{CO}	x_{CO_2}	x_{H_2}	x_{H_2O}	x_{N_2}	x_{O_2}	p	R_g	T	ρ
SS1	2191.9	0.0246	1.0000	0	0	0	0	0	0	101325.0	519.4	298.0	0.6547
SS2	2601.5	0.0246	1.0000	0	0	0	0	0	0	526890.0	519.4	402.1	2.5227
SS3	3109.6	0.0246	1.0000	0	0	0	0	0	0	526890.0	519.4	540.9	1.8754
SS4	2262.9	0.0936	0.2857	0	0	0	0.7143	0	0	526890.0	476.8	522.5	2.1150
SS5	2269.7	0.2681	0.0729	0.0138	0.1216	0.1848	0.6068	0	0	526890.0	456.7	873.0	1.3216
SS6	2140.0	0.3490	0	0.0300	0.1518	0.0985	0.7197	0	0	526890.0	402.0	1211.8	1.0815
SS7	2140.0	0.1745	0	0.0300	0.1518	0.0985	0.7197	0	0	526890.0	402.0	1211.8	1.0815
SS8	1336.1	2.6732	0	0.0026	0.0400	0.0085	0.1585	0.6874	0.1031	526890.0	305.0	1211.8	1.4256
SS9	1396.0	2.6875	0	0	0.0515	0	0.1844	0.6850	0.0791	526890.0	304.4	1400.0	1.2362
SS10	1396.0	1.2856	0	0	0.0515	0	0.1844	0.6850	0.0791	526890.0	304.4	1400.0	1.2362
SS11	1291.7	1.2856	0	0	0.0515	0	0.1844	0.6850	0.0791	110646.9	304.4	968.8	0.3752
SS12	1217.9	1.2856	0	0	0.0515	0	0.1844	0.6850	0.0791	110646.9	304.4	689.7	0.5270
SS13	1215.6	1.2856	0	0	0.0515	0	0.1844	0.6850	0.0791	110646.9	304.4	681.0	0.5336
SS14	1210.0	1.2856	0	0	0.0515	0	0.1844	0.6850	0.0791	110646.9	304.4	660.9	0.5499
SS15	2191.9	0.0142	1.0000	0	0	0	0	0	0	101325.0	519.4	298.0	0.6547
SS16	1396.0	1.4019	0	0	0.0515	0	0.1844	0.6850	0.0791	526890.0	304.4	1400.0	1.2362
SS17	1005.1	1.1777	0	0	0	0	0	0.7900	0.2100	101325.0	288.1	298.0	1.1800
SS18	1040.4	1.1777	0	0	0	0	0	0.7900	0.2100	526890.0	288.1	461.1	3.9657
SS19	1115.3	1.1777	0	0	0	0	0	0.7900	0.2100	526890.0	288.1	832.7	2.1959
SS20	1266.9	2.5796	0	0	0.0287	0	0.1027	0.7315	0.1371	526890.0	297.0	1173.0	1.5124
SS21	1280.0	2.4987	0	0	0.0295	0	0.1056	0.7521	0.1128	526890.0	298.2	1211.8	1.4580
SS22	2140.0	0.1745	0	0.0300	0.1518	0.0985	0.7197	0	0	526890.0	402.0	1211.8	1.0815

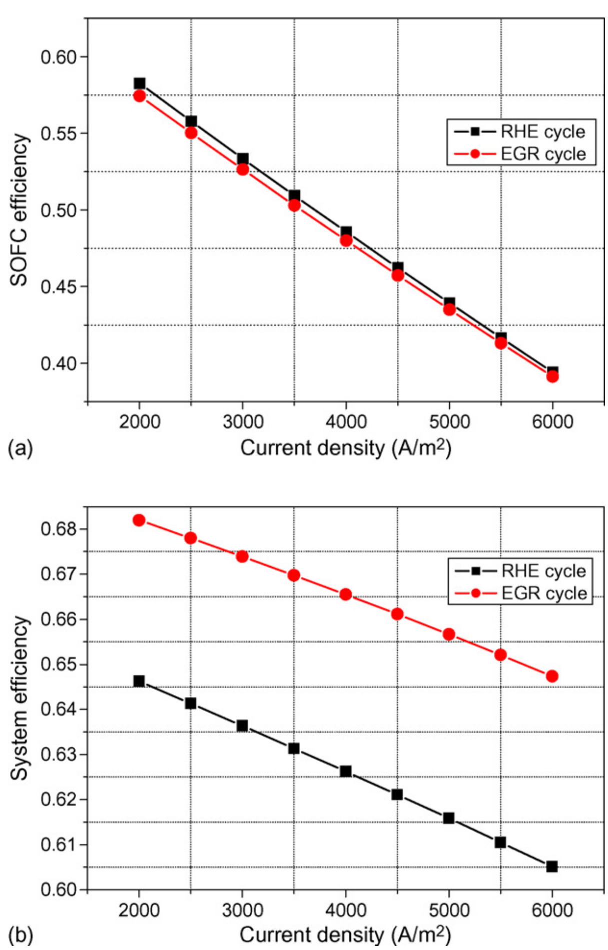

Fig. 4. System performances with variant fuel cell load. (a) SOFC efficiency and (b) system efficiency.

although the fuel cell performance of the EGR cycle was slightly lower than that of the RHE scheme.

The effect of oxygen utilization was studied with constant fuel utilization. Fig. 5(a) shows the SOFC efficiency versus oxygen utilization. The efficiency of the fuel cell is opposite to the oxygen utilization for both the RHE and EGR cycles. This is because the average oxygen molar fraction dropped with increasing oxygen utilization within the fuel cell. Then in Fig. 5(b) the effect of oxygen utilization on the system performance is presented. However, it has an inverse characteristic with that of fuel cell performance curve. The system efficiency is positively dependant on oxygen utilization.

Similar to oxygen utilization, the influence of fuel utilization is investigated based on the assumption of constant oxygen utilization. The other parameters specified in this simulation are given as the same as that applied in the oxygen utilization simulation. The fuel mass flow is set to be a free variable. Fig. 6 shows the fuel utilization effect on the SOFC performance (Fig. 6(a)) and the system performance (Fig. 6(b)). It can be observed that for both the RHE and EGR cycles, the fuel cell efficiency is reduced with increase of fuel utilization. However, as observed in the oxygen utilization study, the system efficiency displays a positively relationship with the fuel utilization. As a result, from the view of system efficiency, a higher value of fuel utilization is recommended while a lower value would be a better choice for the fuel cell.

Fig. 7 draws the curves between the ratios of fuel cell to gas turbine output power and gas utilization for both cycles, showing that with increase of the oxygen utilization, the ratio of the SOFC/GT output power increases (Fig. 7(a)) for both of the two cycle schemes. But in terms of fuel utilization, as shown in Fig. 7(b), the ratio of the SOFC/GT output power decreases with increase of fuel utilization. In addition, the influence amplitude

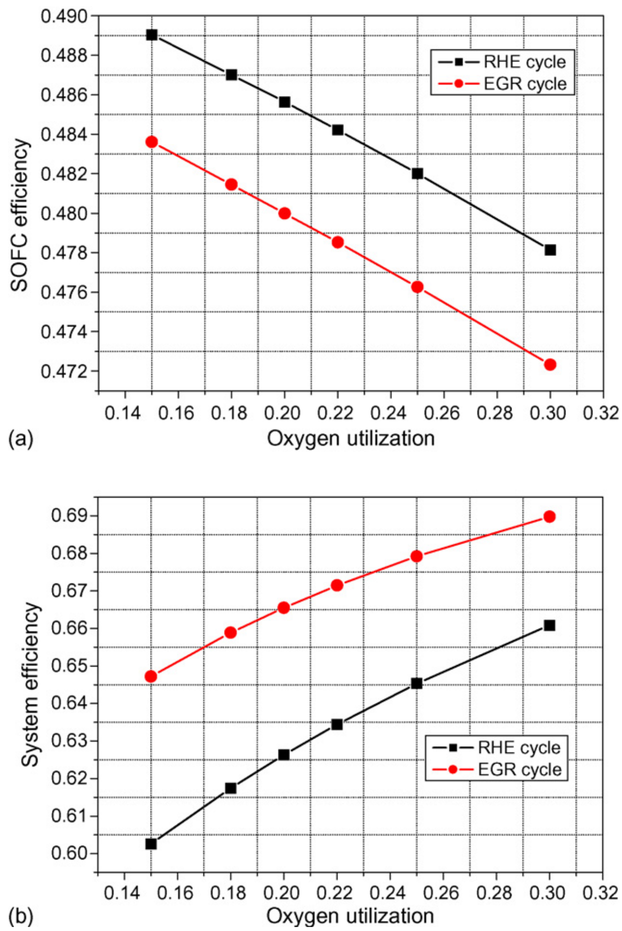

Fig. 5. System performances with variant oxygen utilization. (a) SOFC efficiency and (b) system efficiency.

of oxygen utilization on the ratio of the SOFC/GT output power is more obvious than that of fuel utilization.

3.4. Effect of operating temperature

The effect of the fuel cell inlet temperature and turbine inlet temperature on the RHE and EGR cycle efficiencies is studied in this section. The turbine inlet temperature is set to be 1300 K for the RHE cycle and 1400 K for the EGR cycle in the simulation of variable fuel cell inlet temperature. Similarly, the fuel cell inlet temperature is set to a constant value of 1173 K while the turbine inlet temperature changes. The values of other parameters are consistent with the design point given before. Four cases have been distinguished depending on the variation of inlet temperature: simultaneous variation of the anode and cathode side inlet temperature (case 1), only anode side inlet temperature varied (case 2), only cathode side inlet temperature varied (case 3) and turbine inlet temperature varied (case 4). The results are shown in Table 4, in which the first column of shows the reference value obtained from the design point. When only the anode side inlet temperature increases (see the third column—case 2), the system efficiency is raised for both the RHE and EGR cycles. However, the RHE cycle system efficiency decreases if the cathode side inlet temperature increases (see the fourth column—case 3). If case 1 occurs, i.e. both anode side and cathode side inlet temperature increase 20 K, for EGR cycle, the system efficiency is improved by about 0.4%, which is better than for RHE cycle system of only 0.1%. When the turbine inlet temperature increases, both of the cycle system efficiencies decrease (see the fifth column—case 4). The system efficiency of the EGR cycle decreases about 0.5%, which is higher than that of 0.13% for RHE cycle system if the TIT increases 20 K.

3.5. Effect of gas turbine components performance

Finally, the effect of the gas turbine component efficiencies including the air compressor, turbine and recuperator on the system performance was studied. The system efficiency was firstly calculated based on the design point as mentioned in Section 3.4 as the reference value, which is given as the first column in Table 5. Then the efficiency of each gas turbine component is raised by 2%, the resulted system efficiencies are presented in Table 5. Based on the results, it can be concluded that the efficiency of the hybrid systems are most sensitive to the turbine efficiency. For the recuperator component HX2 and air compressor CP2, their effect on the system performance is comparable. In addition, we can find that the effect of gas turbine component

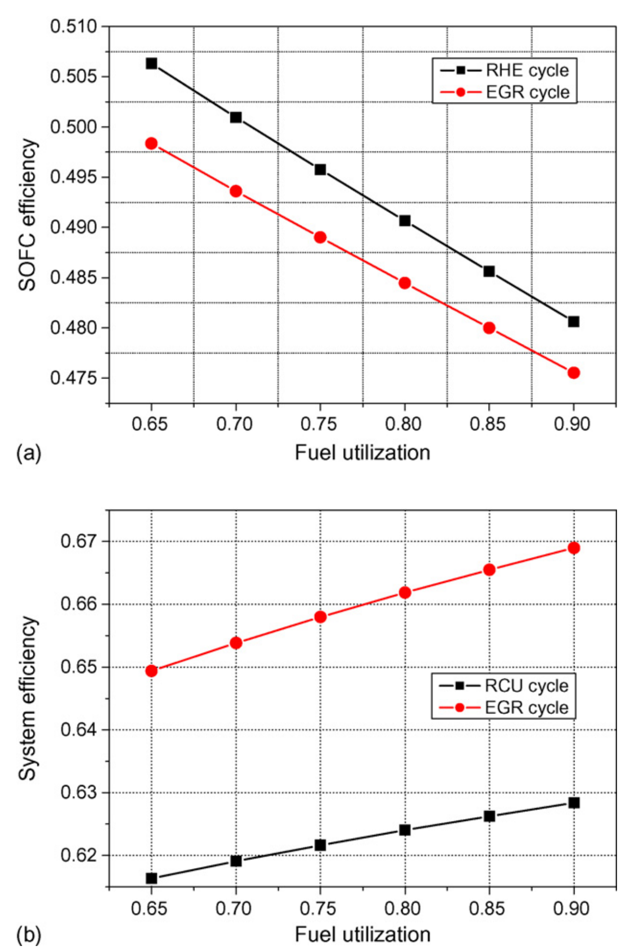

Fig. 6. System performances with variant fuel utilization. (a) SOFC efficiency and (b) system efficiency.

Table 4
Effect of fuel cell operating temperature and turbine inlet temperature

	Datum	T^{in}_{anode} and $T^{in}_{cathode}$		T^{in}_{anode}		$T^{in}_{cathode}$		TIT	
		+20 K	−20 K	+20 K	−20 K	+20 K	−20 K	+20 K	−20 K
Temperature (K)		1193	1153	1193	1153	1193	1153		
η_{SYS} (%) RHE	62.6274	+0.096	−0.16	+0.29	−0.35	−0.19	+0.19	−0.13	+0.13
η_{SYS} (%) EGR	65.2410	+0.38	−0.42	+0.26	−0.32	+0.13	−0.48	−0.5	+0.54

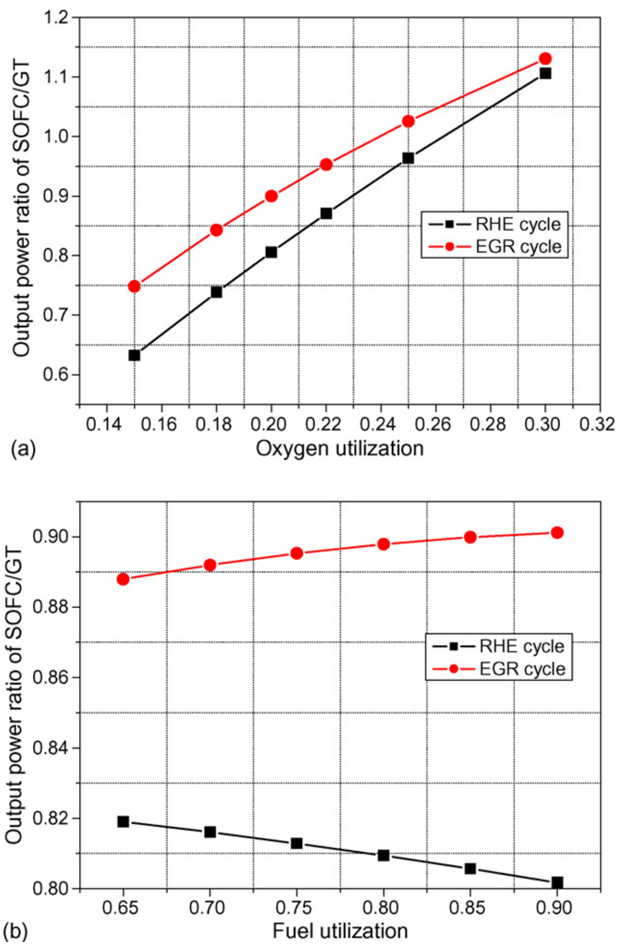

Fig. 7. Effects of oxygen utilization and fuel utilization on the ratio of SOFC/GT output power. (a) Oxygen utilization effect and (b) fuel utilization effect.

Table 5
Effect of gas turbine components efficiency

	Datum	η_{CP} +2%	η_{TB} +2%	ε_{HX1} +2%
η_{SYS} (%) RHE	62.6274	+0.38	+0.72	+0.44
η_{SYS} (%) EGR	65.2410	+0.013	+0.67	+0.011

performance in the RHE cycle is more obvious than that in the EGR cycle on system performance.

4. Conclusion

The cycle schemes for the exhaust gas recirculated (EGR) and the recuperative heat exchanger (RHE), which are labeled according to the air reheating method, are proposed and simulated with the simulation tool software Aspen Custom Modeler. The system efficiency of the EGR air reheating cycle was found to be higher than that of the RHE system. Moreover, the EGR cycle allows the system to operate at a higher pressure ratio, which can further improve the system efficiency.

Based on the simulation results, the influence of the fuel cell oxygen utilization, fuel utilization, operating temperature and efficiencies of gas turbine components on the system performance have been discussed. High levels of SOFC fuel utilization and oxygen utilization would result in a drop of the fuel cell efficiency for both the RHE and EGR cycle systems, whereas the hybrid system efficiency would be raised as the fuel utilization and oxygen utilization increased. The ratio of the SOFC/GT power output is positively correlated with oxygen utilization and fuel utilization for the RHE cycle. However, if we increase the fuel utilization in the EGR cycle system, the ratio of the SOFC/GT power output then decreases, which is opposite to the effect of the oxygen utilization. The effect of the oxygen utilization is more obvious than that of fuel utilization. Additionally, the effect of operating temperature was studied by changing the fuel cell inlet temperature and the turbine inlet temperature. The system efficiency would be improved if the anode side of the fuel cell inlet temperature is increased. For the RHE cycle, the system efficiency was lowered as the cathode side inlet temperature increased, which is reversed for the EGR cycle system. The change of turbine inlet temperature has more of an effect on the system efficiency for the EGR cycle than for RHE cycle, which is increased as TIT decreases. The assessment of the gas turbine component effects indicate that the system efficiency is relatively insensitive to the efficiency of the air compressor and air preheater component recuperator. The turbine efficiency played, however, a stronger influence on system performance. Optimizing the gas turbine components performance in an RHE cycle therefore would achieve higher system than in the EGR cycle.

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