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Optimum selection of the heat exchangers mid-temperatures for SOFC reactants in a hybrid system

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Abstract
Increasing efficiency and decreasing cost are the main purposes in the design of the power generation systems. In this study two hybrid systems: solid oxide fuel cell (SOFC)-gas turbine (GT) and SOFC-GT-steam turbine (ST); are considered. Increasing the SOFC input temperature causes thermodynamics improvement in the hybrid system operation. For this purpose, using two set of SOFC reactants heat exchangers (primary heat exchangers and secondary heat exchangers) are recommended. Selection of The primary heat exchangers output temperature and therefore the secondary heat exchangers input temperature (heat exchangers mid-temperatures) influences on the thermodynamics and economics operation of the hybrid system. This work shows that the annualized cost (ANC) and the levelized cost of energy (LCOE) act in conflict with each other. The MatLab genetic optimization algorithms are used to obtain the optimum solutions. The maximum achievable efficiency is 0.599. Also results show that the heat exchangers mid-temperature of air has the main role in the operation of the hybrid system.

Keywords: heat exchanger; SOFC; gas turbine; steam turbine; multi-objective optimization

Introduction
Finding an appropriate way for efficient power generation with low emissions has become a matter of issue. The fuel cells are considered to be a suitable candidate for future power production owing to its high-thermal efficiency and low pollutant emissions [1]. Among various types of fuel cells, solid oxide fuel cell is more suitable for distributed power generation because it has high efficiency, fuel flexibility and sufficiently high operating temperature which make it a key candidate for combination with gas turbine leading to additional electricity generation [2]. SOFC modeling and SOFC integrated configurations has been studied in Refs. [3,4]. In addition, a lot of researches have been carried out on modeling of hybrid SOFC-GT systems [5,6], part load operation of SOFC-GT [7], and SOFC-GT for combined heat and power generation [2].

Economic analyzing could also be taken into account when a power generation system is analyzed. Thermo-economic method is a suitable method for analyzing the system from both thermodynamic and economic points of view. Cheddie [8] considered a thermo-economic optimization analysis on an indirectly coupled SOFC-10 MW gas turbine hybrid system. Cheddie and Murray [9] also performed the same analysis on a SOFC-GT system with semi-direct coupling and anode recycling. Santin et al. [10] considered a thermo- economic analysis of SOFC-GT system that uses liquid fuels.

The thermodynamics objective functions are usually in conflict with the economic objectives functions. Therefore multi-objective optimization method is used to obtain the optimum solutions. Autissier et al. [11] was considered multi-objective thermo-economic optimization of a SOFC-GT hybrid system that in which maximization of the electrical efficiency and minimization of investment cost were considered as objectives. Palazzi et al. [12] also considered a similar study on a planar SOFC system for stationary applications. Environmental effects of power generating systems have also been taken into account in the recent studies. Ahmadi and Dincer used an exergoenviromental analysis on a gas turbine power system [13].

The present study uses MatLab optimization algorithms to give the optimum thermo-economic solutions for a SOFC-GT hybrid system and a SOFC-GT-ST hybrid system. In these hybrid systems, two set of heat exchangers are considered to heat the SOFC reactants. Using these set of heat exchangers provide the possibility to increase the SOFC input temperature as much as desirable and so improving the performance of the hybrid systems. The optimization solutions give the optimum value for the heat exchangers mid-temperatures.

Mathematical modeling of the components
The fuel cell used in this study is a type of tubular solid oxide fuel cell with internal reforming [14]. For a fuel cell fed by a conventional fuel like natural gas, reforming is needed to convert the fuel into hydrogen. The produced hydrogen by reforming and shifting reactions with the available oxygen in the air participates in the electrochemical reaction. The power generated by SOFC can be calculated based on the real voltage of the fuel cell by follow equations.

$$I_{tot} = 2Fz \quad (1)$$

$$Power_{DC-tot} = V_{cell} I_{tot} \quad (2)$$

$$Power_{AC-tot} = Power_{DC-tot} \times \eta_{inv,FC} \quad (3)$$

where I_{tot} is the total current of the fuel cell, $\eta_{invt,sofc}$ is the coefficient of inversion of direct to alternative voltage in the fuel cell, z is the molar rates of the electrochemical reaction progress and F is the Faraday's constant.

In the gas turbine, by knowing the turbine inlet temperature, pressure ratio, and the isentropic efficiency of gas turbine, the value of actual work and exhaust gas temperature can be calculated according to

$$\frac{T_{out,s}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}} \quad (4)$$

$$\eta_{GT} = \frac{w_{GT}}{w_{GT,s}} = \frac{\bar{h}_{out}-\bar{h}_{in}}{\bar{h}_{out,s}-\bar{h}_{in}} = \frac{T_{out}-T_{in}}{T_{out,s}-T_{in}} \quad (5)$$

$$\dot{W}_{GT} = \dot{n} \times \left(\bar{h}_{out} - \bar{h}_{in}\right) \quad (6)$$

Because only a portion of inlet fuel and air are consumed in the fuel cell, the role of after burner (AB) is to increase the system efficiency and reduce the pollution. The outlet gases of the fuel cell, which consist of steam, carbon dioxide, carbon monoxide, hydrogen, and methane in the anode side, and oxygen and nitrogen in cathode side, are reacted in the after burner

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \quad (7)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (8)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (9)$$

All of the above reactions are exothermic and cause the temperature rise of outlet gases of the after burner. The temperature of outlet gases of the after burner can be calculated by the energy conservation equation and considering the efficiency of the after burner as follows

$$\sum(\dot{n}\bar{h})_{in} - \sum(\dot{n}\bar{h})_{out} - \dot{Q}_{loss} = 0 \quad (10)$$

where $\dot{Q}_{loss}$ is the heat losses of the after burner, its value depending on the efficiency of the combustion.

The temperature of outlet gases from the heat exchanger is calculated based on effectiveness-number of transfer unit method

$$\varepsilon_{HE} = \frac{(\dot{n}\bar{c}_p)_c(T_{out,c}-T_{in,c})}{(\dot{n}\bar{c}_p)_{min}(T_{in,h}-T_{in,c})} = \frac{(\dot{n}\bar{c}_p)_h(T_{in,h}-T_{out,h})}{(\dot{n}\bar{c}_p)_{min}(T_{in,h}-T_{in,c})}$$

$$\dot{Q} = \varepsilon_{HE} \times (\dot{n}\bar{c}_p)_{min} \times (T_{in,h} - T_{in,c}) = (\dot{n}\bar{c}_p)_c(T_{out,c} - T_{in,c}) = (\dot{n}\bar{c}_p)_h(T_{in,h} - T_{out,h}) \quad (11)$$

The super-heated steam enters to the steam turbine to generate power. The governing equations of the steam turbine are

$$\eta_{ST} = \frac{w_{ST}}{w_{ST,s}} = \frac{\bar{h}_{out}-\bar{h}_{in}}{\bar{h}_{out,s}-\bar{h}_{in}} \quad (12)$$

$$\dot{W}_{ST} = \dot{n} \times \left(\bar{h}_{out} - \bar{h}_{in}\right) \quad (13)$$

The HRSG (heat recovery steam generation) model calculates the steam flow rate and the output steam temperature at the HRSG exit. Also, it sizes the different types of heat exchangers included in the HRSG. The energy balances on the gas and steam sides are

$$\dot{Q}^{gas} = \dot{n}_{gas}\bar{c}_{p,gas}(T_{in} - T_{out}) \quad (14)$$

$$\dot{Q}^{steam} = \dot{n}_{steam}\bar{c}_{p,steam}(T_{out} - T_{in}) \quad (15)$$

The heat transfer rate is determined from Eq. (43), and since the gas and steam heat transfer rates are equal to each other, Eq. (44) is solved for the steam flow rate. Using simple energy balances as the preceding ones, all temperatures and heat transfer rates can be calculated for all the heat exchangers. For the geometric models of the heat exchangers, the effectiveness-number of transfer unit method is used.

If the heat of the exhaust gases from the gas turbine is not enough to steam generation, a super heater (SH) is used to generate the needed steam for the steam turbine.

Objective functions

Considering the total hybrid system as a control volume, the electrical efficiency and net output power are obtained by the following equations

$$\eta_{elec} = \frac{\dot{W}_{net}}{\dot{n}_{fuel} \times LHV} \quad (16)$$

$$\dot{W}_{net} = \sum \dot{W}_{generate} - \sum \dot{W}_{consume} \quad (17)$$

In finance, the annualized cost is the cost per year of owning and operating an asset over its entire lifespan. In order to calculate ANC, annualized initial capital cost, annualized operating cost, and annualized maintenance cost will be added [15]. Since life of different components are gotten equal, replacement costs are not considered.

Annualized initial capital cost:

$$C_{acap} = C_{cap}.CRF(i, R_{proj}) \quad (18)$$

C_{acap}, C_{cap}, CRF, i, R_{proj} are annualized initial capital cost, initial capital cost, capital recovery factor, real interest rate, and system lifespan respectively.

Real interest rate: $i = \frac{i'-f}{f+1}$ (19)

i' and f are nominal interest rate and inflation that are gotten 0.2 and 0.15, respectively.

Capital recovery factor:

$$CFR(i, R_{proj}) = \frac{i(1+i)^{R_{proj}}}{(1+i)^{R_{proj}}-1} \quad (20)$$

The provided equations in the Arsalis paper [16] are used to estimation initial capital cost, maintenance cost, and operating cost of the hybrid system components.

Results and Discussion

Fig. 1 shows the different configurations. Configuration b uses the GT output for heating the SOFC input reactants. In this configuration, the SOFC input temperature cannot rise to the desired value because it depends on the GT output temperature. The SOFC input temperature influences on the operating temperature of the SOFC. If the SOFC input temperature increases, the operating SOFC temperature will increase. Therefore the SOFC input temperature is an effective parameter on the operation of the SOFC and also the operation of the hybrid system. In the configuration (a), SOFC reactants heat with the GT output in the primary heat exchangers and then heat to a desired value with the after burner output in the secondary heat exchangers. The heat exchangers mid-temperatures influences on the GT input temperature and also the operation of the hybrid system. In the present work, the optimum heat exchangers mid-temperatures are optimized to increase the hybrid system efficiency and decrease the hybrid system annualized cost. The MatLab genetic optimization algorithms are used to obtain the optimum solutions. The variable parameters are the fuel, water, and air heat exchangers mid-temperature.

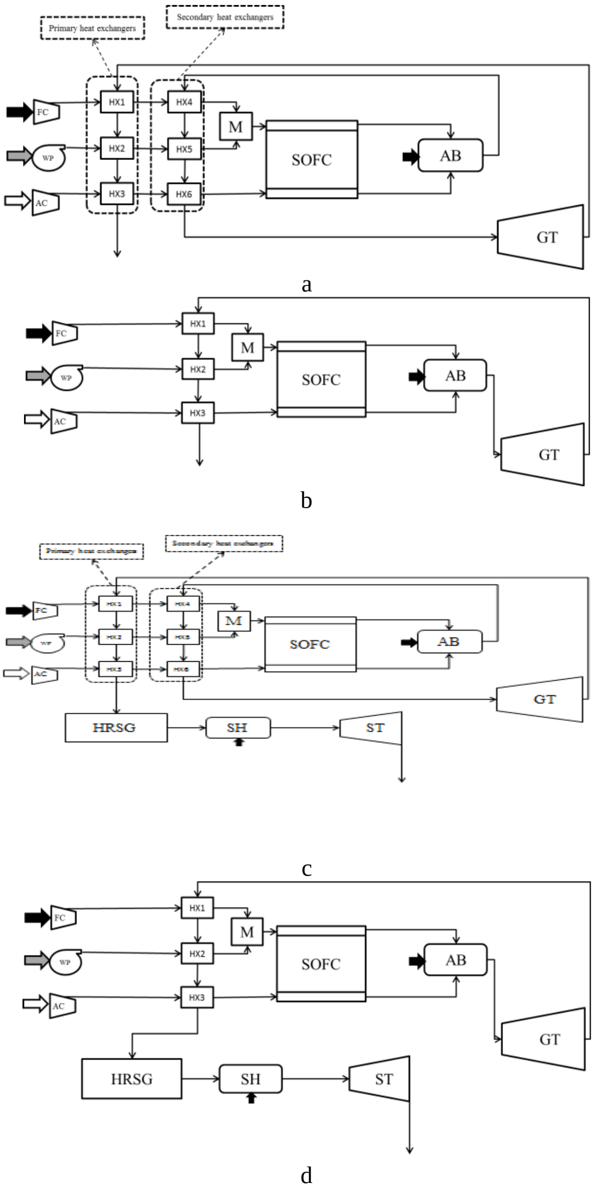

Fig.1 different configurations of the hybrid systems

Table 1. the solid oxide fuel cell operating parameters

SOFC input temperature(K)	SOFC operating temperature(K)	SOFC operating voltage(V)	SOFC power generation(kW)
1000	1167	0.66	1143
1100	1233	0.72	1229
1150	1272	0.74	1254

Table 2. characteristics of thermodynamics optimum solution, multi-objective optimum solution, and economic optimum solution

		Efficiency	Annualized cost ($/year)	Fuel heat exchangers mid-temperature(K)	Water heat exchangers mid-temperature(K)	Air heat exchangers mid-temperature(K)
SOFC-GT	Point A	0.583	299870	920	937	1088
	Point B	0.537	291495	999	873	831
	Point C	0.491	282857	800	700	600
SOFC-GT-ST	Point D	0.595	307890	972	856	1093
	Point E	0.561	302122	885	775	861
	Point F	0.524	294737	800	700	600

First, the SOFC-GT hybrid system is studied. With increasing the SOFC inlet temperature, the operating temperature and voltage of the SOFC will increase. The increase in SOFC operating voltage causes the increase in the SOFC power generation and so the increase in the hybrid system efficiency. Table 1 shows the SOFC operating temperature and voltage for three different value of SOFC inlet temperature. If the GT output is used to entirely heat the SOFC reactants, the SOFC input temperature cannot rise as much as desirable. The present work recommends that the GT output is used to primary heating and the after burner output is used to the final heating for reaching the desired SOFC input temperature. With using the after burner output for SOFC reactants heating, the GT input temperature decreases and it causes the decrease in the GT power generation. But the increase in the SOFC power generation due to increscent of the SOFC operating temperature causes the increase in the total efficiency. Now assume that the SOFC input temperature is constant. Therefore, the heat exchangers mid-temperatures do not influence on the SOFC operation but they influence on the operation of the GT and also the hybrid system. Hence choosing a suitable value for the heat exchangers mid-temperature is important. Whatever the heat exchangers mid-temperatures are higher, the GT input temperature and so the hybrid system efficiency are higher. On the other hand, whatever the heat exchangers mid-temperatures is lower, the difference in the temperature of the hot and cold heat exchangers fluids disport suitable between primary and secondary heat exchangers. Therefore the heat exchanger needed surface and the annualized cost will decrease. Hence the change of cost and the change of efficiency with the heat exchangers mid-temperatures are in conflict with each other. To obtain the optimum heat exchangers mid-temperatures, a multi-objective optimization method must be used. In this study, The MatLab NSGAII algorithm is used for the multi-objective optimization.

Fig. 2 shows the Pareto frontier of the SOFC-GT hybrid system for three different SOFC input temperature. It is obvious that the increase in the SOFC input temperature can generate the possibility to reach to higher the hybrid system efficiency. As the fig. 2 shows the annualized cost increases with the increase in the hybrid system efficiency. Three points are selected in the pareto frontier of the 1100K SOFC input temperature. Point A is the thermodynamics optimum solution. Point C is the economic optimum solution. Point B is the multi-objective optimum solution. The heat exchangers mid-temperatures of these points are shown in table 2.

If a steam turbine is added to the SOFC-GT hybrid system, it is possible to heat the ST feed water with the primary heat exchangers output. Then the ST feed water enters to a super-heater and with consume some fuel reaches to the needed condition for generating power in the steam turbine. Using the ST can improve the hybrid system efficiency. The schematic of this hybrid system are shown in fig.1c. As the SOFC-GT hybrid system, the pareto frontier of the SOFC-GT-ST hybrid system are obtained. The pareto frontiers of the hybrid system a and c for the 1100K SOFC input temperature are compared in fig.3. With adding the steam turbine, the efficiency and also the annualized cost will be increased. As an example, for the thermodynamics optimum solutions, the efficiency increases approximately 1.5 percent and also the annualized cost increases approximately 8000$/year. Fig.4 shows the pareto frontiers of the SOFC-GT-ST hybrid system for three different SOFC input temperature. With increasing the SOFC input temperature, the efficiency and also the annualized cost will be increased. The reason of annualized cost increment is the increase in the heat exchanger surface and the increase in the SOFC operating temperature. Three points are selected in the pareto frontier of the 1100K SOFC input temperature. Point D, E, and F are the thermodynamics optimum solution, multi-objective optimum solution, and the economic optimum solution, respectively. The heat exchangers mid-temperatures of these points are shown in table 2.

The thermodynamics optimum solution of the hybrid system with six heat exchangers (six-HXs system) is compared with the hybrid system with three heat exchangers (three-HXs system) in table 3. Results show while the SOFC input temperature (1000K) is same for six-HXs system and three-HXs system, the three-HXs system causes higher efficiency and lower annualized cost. But the efficiency difference and the annualized cost difference are very small. In the six-HXs system, the hot and cold fluid temperature difference is greater and therefore the heat exchanger surface decreases. This surface area reduction compensates cost of the three additional heat exchangers partly. In order to better understand the operation of the six-HXs system; the total power, the power generation of the hybrid system components, GT input and output temperature, the ST HRSG input temperature, and the heat exchangers mid-temperatures of the SOFC-GT-ST hybrid system (system c) are shown in figs. 5, 6, 7 for the solutions of the 1100K SOFC input temperature Pareto frontier.

Table 3. efficiency and annualized cost of three-HXs system and six-HXs system for 1000K SOFC input temperature

		Efficiency	Annualized cost ($/year)
SOFC-GT	Three-HXs system	0.548	280193
	Six-HXs system	0.543	280584
SOFC-GT-ST	Three-HXs system	0.569	289937
	Six-HXs system	0.566	290949

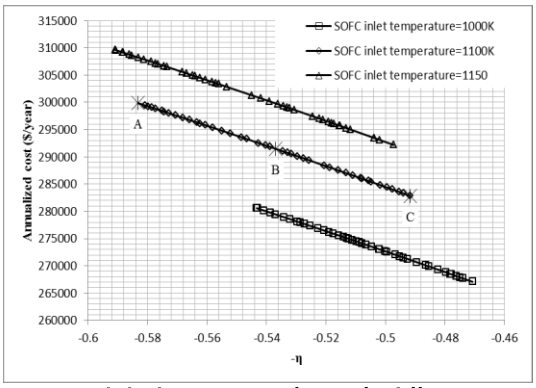

Fig.2 SOFC-GT hybrid system pareto frontier for different input SOFC temperature

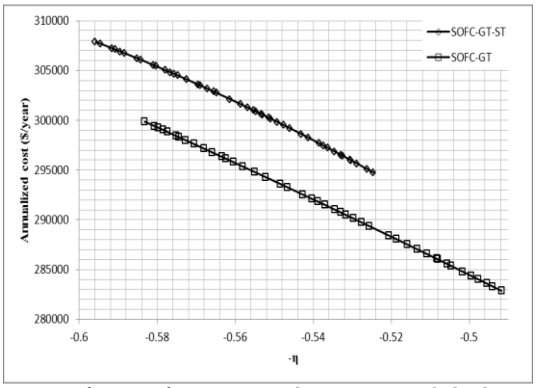

Fig.3 pareto frontier of SOFC-GT and SOFC-GT-ST hybrid systems with six heat exchangers

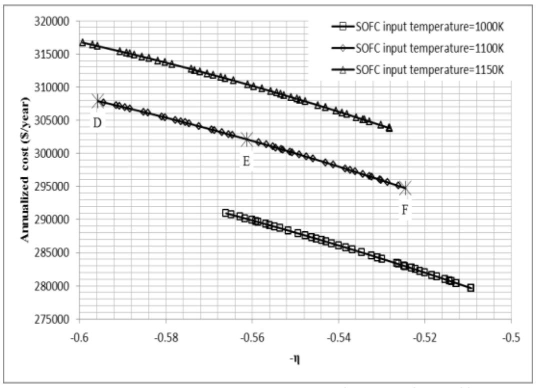

Fig. 4 SOFC-GT-ST hybrid system pareto frontier for different input SOFC temperature

Fig. 5 shows the total power and the power generation of the hybrid system components. Since the SOFC operation voltage is constant, the power generation of different pareto solutions are constant while the efficiency decreases. The GT power generation decreases and the ST power generation increases while the efficiency decreases. As shown in fig. 6, the reason of the GT power reduction is the decrease in the GT input temperature. Visa versa, the ST power generation increases because the ST input temperature increases. The heat exchangers mid-temperatures are shown in fig. 7. The heat exchangers mid-temperature of fuel and water is chosen non-uniform between 700-1000K. The heat exchangers mid-temperature of air decreases as the efficiency decreases. Comparison the needed heat of the reactants shows that the most portion of heat is needed for the air heating. Therefore the heat exchangers mid-temperature of air has the main role in the operation of the hybrid system. For this reason the heat exchangers mid-temperature of fuel and water is chosen non-uniform. With decrease in the heat exchangers mid-temperature of air, the portion of the after burner output in the air heating increases and so the GT input temperature decreases. On the other hand, with decrease in the heat exchangers mid-temperature of air, the portion of the GT output in the air heating decreases and so the ST input temperature increases.

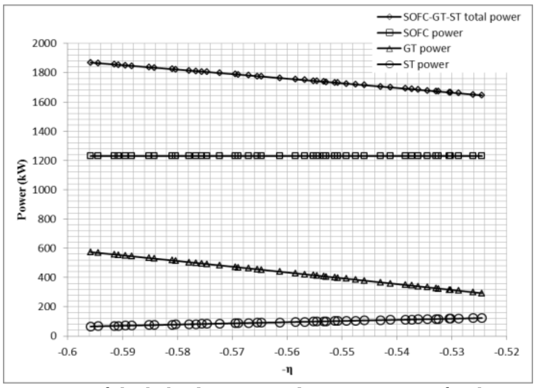

Fig. 5 power of the hybrid system and its components for the pareto solutions of configuration c

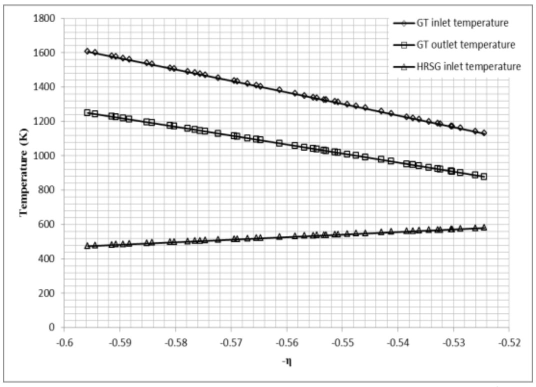

Fig. 6 GT input, GT output, and HRSG input temperatures for the pareto solutions of configuration c

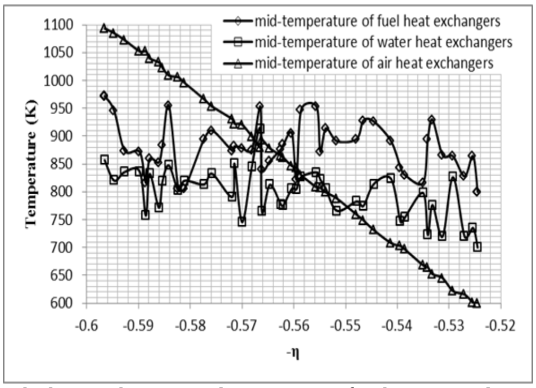

Fig.7 the heat exchangers mid-temperatures for the pareto solutions of configuration c

Conclusions

In this study, two hybrid systems are considered and was effort to improve the thermodynamics and economic operation of them. Increasing the SOFC inlet temperature can increase the operating temperature and voltage of the SOFC and so the hybrid system efficiency. If the GT output is used to entirely heat the SOFC reactants, the SOFC input temperature cannot rise as much as desirable. Therefore, the GT output is used to primary heating and the after burner output is used to the final heating for reaching the desired SOFC input temperature. Adding the steam turbine increases the hybrid system efficiency and also the annualized of the hybrid system. For the same SOFC input temperature, the three-HXs system causes higher efficiency and lower annualized cost, But the efficiency difference and the annualized cost difference are very small. The heat exchangers mid-temperature of air has the main role in the operation of the hybrid system. With decrease in the heat exchangers mid-temperature of air, the portion of the after burner output in the air heating increases and the portion of the GT output in the air heating decreases, therefore the GT input temperature decreases and the ST input temperature increases.

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