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Thermo-economic analysis of a NG-fueled SOFC-HCCI engine hybrid energy conversion system as distributed power plant with high efficiency

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ABSTRACT

Solid oxide fuel cell (SOFC) was integrated with internal combustion engine (ICE) due to its high operating temperature for improving the energy conversion efficiency in this work. In the SOFC-ICE hybrid energy conversion system, the SOFC anode off-gas with high temperature and combustible fuels is used as the ICE fuel for additional power generation. To evaluate the thermo-economic performance, the thermo-economic model of the hybrid system is developed for the economic analysis. The results showed that the specific electric energy cost (SEEC) of the hybrid system is 3.75 ¢/kWh, which is lower than that of a standard power plant. Through the further analysis, the capital investment cost of the system with the net output power of 470 kW is 50.5 k$, which includes the capital cost of auxiliary devices such as heat exchanger and compressors. In addition, the SOFC accounts for about 35% of the system's capital cost. The annual cost of the system under the cycle life of 10 years is calculated to be approximately 15.6 k$. Moreover, the influence of operating parameters on thermo-economic performance of the hybrid system is also investigated to optimize the thermo-economic performance. Finally, the corresponding payback period of this system is approximately 6.8 years and the annual return on investment is 4.6%. These results reveal that the proposed NG-fueled SOFC-HCCI engine hybrid system presents a broad market prospect in the practical applications.

Keywords: SOFC, engine, hybrid power system, thermo-economic analysis

NONMENCLATURE

Abbreviations	
SOFC	Solid oxide fuel cell
DIR	Direct internal reforming
GT	Gas turbine
ICE	Internal combustion engine
HEX	Heat exchanger
HCCI	Homogeneous charge compression ignition
NG	Nature gas
WGS	Water gas shift reaction
SEEC	Specific electric energy cost
FC	Fuel cell
MSR	Methane steam reforming
ICE	Internal combustion engine
inv	Inverter
comp	Compressor
aux	Auxiliary equipment
Symbols	
C	Capital cost, $
$\dot{W}$	Power, kW
A	Area, m^2
T	Temperature, K
$\dot{C}$	Annual cost. $

1. INTRODUCTION

With the rapid development of society, it is very essential to come up with an efficient and clean way for energy utilization. As an innovative power generation technology, fuel cell (FC) has attracted more and more attention due to its high efficiency, low emission and no noise [1]. Solid oxide fuel cell (SOFC) has to work at relatively high operating temperatures ranging from 650 to 1000 °C [2]. The high operating temperatures enable the reforming reaction and water gas shift (WGS) reaction to occur inside the SOFC, which could convert the hydrocarbon fuels such as natural gas (NG),

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methanol, biomass gas and other fuels into hydrogen for electrochemical reaction [3]. Therefore, the SOFC is highly adaptable and robust to fuel flexibility. Owing to the high operation temperatures and the large exothermic heat (242 kJ/mol) of the electrochemical reaction, the SOFC can integrate with other energy conversion systems for improving its energy conversion efficiency [4]. The advantages of the SOFC hybrid system can be categorized as follows: (a) recycling the unreacted FC anode off-gas and reducing the emissions, (b) further enhancing the performance of the hybrid system by waste heat recovery, (c) generating the additional power and improving the energy conversion efficiency [5].

In this context, the SOFC hybrid power generation system with the organic Rankine or Otto cycle as the bottom thermodynamic cycle is reported intensively. For example, SOFC-gas turbine (GT) hybrid power generation system has been proposed for years. However, the power capacity of GT is generally the order of magnitude of MW-scale which does not match well with the power capacity of SOFC (kW-scale) in fact. Compared to GT, the power capacity of internal combustion engine (ICE) is much lower, indicating the SOFC-ICE hybrid system maybe exhibit the better coupling characteristics and compatibility than the SOFC-GT hybrid system. In addition, an engine exhibits more stable and faster start-up performance than the GT in harsher environments. Therefore, the SOFC-engine hybrid power generation system has been attracting attention due to its potential application such as stationary power generation, transportation vehicle and military equipment power plant.

In recent years, Hosseinpour et al. [6] proposed a cogeneration system based on a methane-fed SOFC integrated with a Stirling engine. Then the influences of the key parameters on the system performance were further investigated. After the performance optimization, the energy conversion efficiency of the hybrid system was found to be 76.32%, which is 24.61% higher than that of a stand-alone SOFC power plant under the same conditions. Chuahy et al. [7] adopted the method of computational system optimization to explore the efficiency potential of an electrochemical combustion combined system for distributed power generation. It was concluded that the system is capable of achieving the electrical efficiency over 70%. Kang et al. [8] developed the dynamic model of a SOFC-engine hybrid system to evaluate the dynamic behaviors. The report lays out a theoretical foundation for the operating strategies of SOFC-engine hybrid system under different transient conditions. Park et al. [9] carried out a comparative study on the performance between SOFC-ICE and SOFC-GT hybrid power systems. The comparison results showed that the energy conversion efficiency of the SOFC-engine hybrid system is increased by 0.9% and the energy cost is reduced by 7.6% compared with the SOFC-GT hybrid system.

In short, the SOFC-engine hybrid power system is viewed as a promising energy conversion device with high efficiency. However, it is generally difficult to use SOFC anode off-gas as engine fuel because the off-gas is a thin fuel in fact. Homogeneous charge compression ignition (HCCI) is a new kind of combustion mode for the engine based on Otto reciprocating gasoline engine, which enables to make the best use of the lean fuel for combustion [10]. Therefore, our work proposes a novel NG-fed SOFC-HCCI engine hybrid system using the HCCI engine as bottom cycle to utilize the SOFC off-gas for additional power generation. Furthermore, the thermo-economic performance of the SOFC-HCCI engine hybrid system is evaluated systematically.

2. SYSTEM MODELING

2.1 System description

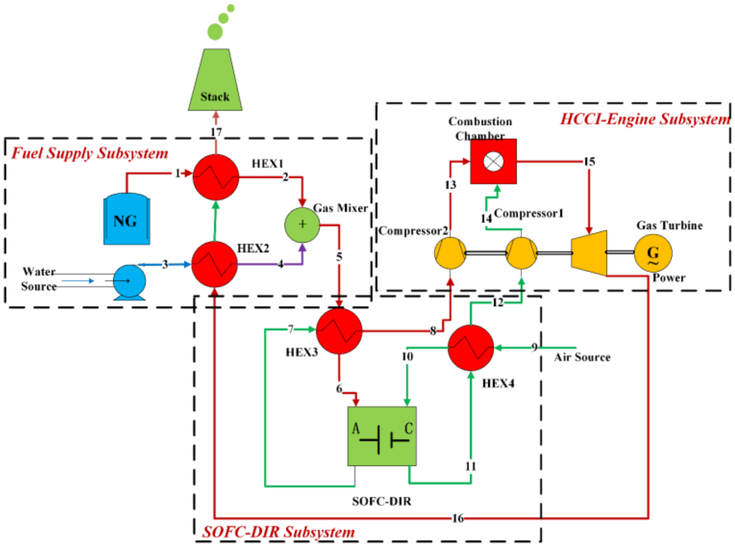

Fig. 1. The layout of the SOFC-HCCI engine hybrid power generation system

The NG-fueled SOFC-HCCI engine hybrid system consist of three subsystem, which are SOFC-DIR, HCCI engine and fuel supply subsystem, as shown in Fig. 1. The SOFC-DIR subsystem aims to generate most of the system power and meanwhile produce the fuel for the downstream engine via the methane steam reforming (MSR) and water gas shift (WGS) reactions. The role of the HCCI engine subsystem is to make full use of the off-gas for additional power generation. The fuel source NG and water are heated respectively by HEX1 and HEX2 to produce the gas mixture of NG and steam via a gas mixer. Then, the mixture after being furthered heated by HEX3 is fed into the SOFC-DIR as anode fuel. Similarly, the air after being heated by HEX4 with waste heat from the cathode off-gas is fed as cathode oxidant. The MSR reaction converting the mixture gas into water gas (H_2 and CO), takes place in the SOFC-DIR due to its high operating temperatures. Then the component CO can be further converted into CO_2 and H_2 via WGS reaction. For the SOFC, the electrochemical reaction between H_2 and O_2 happens to generate the electricity power. In the HCCI engine subsystem, the engine fuel comes from the SOFC anode off-gas (main compositions: CO, CO_2, H_2, and H_2O). First, the fuel is compressed into a combustion chamber by No.2 Compressor to form the high temperature flue gas. The high-temperature flue gas could drive gas turbine to run for additional power generation, which could further improve the energy conversion efficiency of the system.

2.2 Thermo-economic modeling

Because the thermo-economic analysis of the system must be based on the thermodynamic performance of the hybrid system. In our previous study [11], the thermodynamic model of this hybrid system has developed first. Herein, this paper just gives the thermo-economic model of the hybrid system. According to the description of the SOFC-HCCI engine hybrid power system as illustrated in Fig. 1, the hybrid system mainly consists of the components gas turbine, compressors, SOFC-DIR, DC/AC inverter, SOFC auxiliary equipment, and heat exchanger. Table 1 shows the capital investment cost model for all the components involved in the SOFC-HCCI engine hybrid system. In order to accurately reflect the economic performance of SOFC-HCCI engine hybrid system, the capital investment cost of each component is allocated averagely on an annual

Table 1 The capital investment cost model for all the components used in the hybrid system [12, 13]

Capital cost	Description	Capital cost equation
C_{GT}	Cost of gas turbine (\$)	$C_{GT} = \left(-98.328\ln\left(\dot{W}_{GT}\right) + 1318.5\right)\dot{W}_{GT}$
C_{comp}	Cost of compressor (\$)	$C_{comp} = 91562\left(\dot{W}_{comp} / 445\right)^{0.67}$
C_{SOFC}	Cost of SOFC-DIR (\$)	$C_{\mathrm{SOFC}} = A_{cell}(2.96T_{cell} - 1907)$
C_{inv}	Cost of inventer (\$)	$C_{inv} = 10^5(W_{cell} / 500)^{0.7}$
$C_{\mathrm{aux,SOFC}}$	Cost of SOFC auxiliary equipment (\$)	$C_{aux,SOFC} = 0.1C_{SOFC}$
C_{HEX}	Cost of heat exchanger (\$)	$C_{HEX} = 130(A_{HEX} / 0.093)^{0.78}$

Table 2 Different annual cost models of the hybrid system for electricity generation

Annual cost composition	Cost equation	Variable description
Depreciation cost $\dot{C}_{dep}$ (\$/year)	$\dot{C}_{dep} = C_{cap} / n$	*n*: life cycle, 10 years
Operation cost $\dot{C}_{ope}$ (\$/year)	$\dot{C}_{ope} = c\phi N_h$	*c*: fuel cost, 0.124 \$/Nm^3 ϕ : fuel flux, Nm^3/h N_h : Annual operation time, 8760 h
Maintenance cost $\dot{C}_{mai}$ (\$/year)	$\dot{C}_{mai} = (C_{cap}/n) \cdot f_{mai}$	f_{mai} : Maintenance cost factor, 0.06
Investment interest cost $\dot{C}_{\mathrm{int}}$ (\$/year)	$\dot{C}_{\mathrm{int}} = (C_{cap} / n)i$	*i*: Interest rate, 0.0926
Insurance cost $\dot{C}_{ins}$ (\$/year)	$\dot{C}_{\mathrm{ins}} = (C_{cap} / n) \cdot f_{ins}$	f_{ins} : Insurance cost factor, 0.2
Taxation cost $\dot{C}_{tax}$ (\$/year)	$\dot{C}_{tax} = (C_{cap} / n)\, f_{tax}$	f_{tax} : Insurance cost factor, 7.25%

basis. The annual cost of the SOFC-HCCI engine hybrid system includes the following parts: depreciation cost $\dot{C}_{dep}$, maintenance cost $\dot{C}_{mai}$, the annual interest on investment $\dot{C}_{\text{int}}$, the annual insurance $\dot{C}_{ins}$, operation cost $\dot{C}_{Ope}$ and tax cost $\dot{C}_{tax}$. The depreciation cost refers to the gradual loss of the equipment value as it deteriorates with time. Therefore, depreciation cost is averagely distributed over the lifetime of the system. In this study, linear depreciation method is adopted. The lifetime of the hybrid system is considered to be 10 years. Table 2 shows the meaning and equation of each annual cost. Finally, the economic evaluating index, specific electric energy cost (SEEC), is proposed in Eq. (1) to estimate the economy of the hybrid system.

$$SEEC=\frac{\dot{C}_{dep}+\dot{C}_{ope}+\dot{C}_{mai}+\dot{C}_{int}+\dot{C}_{ins}+\dot{C}_{tax}}{(W_{SOFC}+W_{Engine})\cdot N_h} \tag{1}$$

3. RESULTS AND DISCUSSION

3.1 Thermo-economic performance

The thermo-economic analysis is performed when the operating parameters is set as T_{SOFC}=1073 K, steam and carbon ratio *S*/*C*=2.5, and fuel utilization μ=0.75. The SEEC of the SOFC-HCCI engine hybrid power generation system is calculated to be 3.75 ₵/kW h which has a significant decrease when compared to the energy cost (5.46 ₵/kW h) of a standard power plant [14]. By comparison, the SEEC of the SOFC-HCCI engine hybrid system is reduced by about 31%, which indicates that the system is a promising energy conversion device in the market and has a broad market prospect in the future. The components cost of the SOFC-HCCI engine hybrid system and their cost contribution are demonstrated in Fig. 2. The total capital investment cost of the hybrid system is approximately 456 k$, consisting of 139.6 K$ for the SOFC-DIR, 178.6 k$ for the gas turbine, 83 k$ for the inverter, 51.1 k$ for the compressors and 4.016 k$ for the HEXs. The capital investment cost of the two power generation components gas turbine and SOFC-DIR (include its auxiliary equipment) contributes to about 39% and 31% of the total capital cost, respectively. Fig. 3 illustrates the compositions of the annual cost of the SOFC-HCCI hybrid engine system and their cost distribution. The largest annual cost is the operation cost of about 87.6 k$, accounting for 57.3% of the total annual cost. The second largest annual cost is the depreciation cost of about 45.6 k$, which accounts for 29.9% of the total annual cost. In addition, based on the standard of 11.2 ₵/kW h feed-in tariff for natural gas power generation in Shanghai [15], the return period of this system is about 6.8 years, and the annual return on investment is 4.6%.

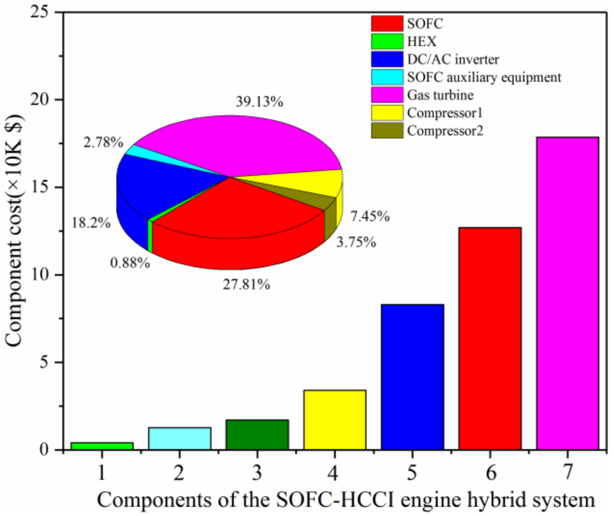

Fig. 2 The annual cost composition of the hybrid system

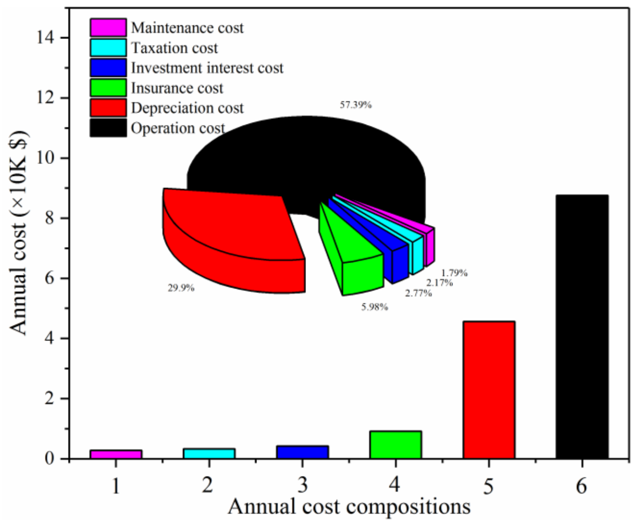

Fig. 3 The annual cost composition of the hybrid system

3.2 Thermo-economic parametric analysis

To achieve the optimal thermo-economic performance for the NG-fueled SOFC-HCCI engine hybrid system, the parametric analysis is further carried out in this work. Fig. 4a displays the effect of the SOFC reforming temperature on the SEEC of the hybrid system. SEEC tends to decrease first and then increase with the improvement of SOFC temperature, and reaches 3.60 ₵/kW h, the minimum value, when the temperature is 1173 K. Different from SEEC, the annual cost increases as the SOFC reforming temperature increases. This is mainly because with the increase of SOFC reforming temperature, the power consumed and the output of

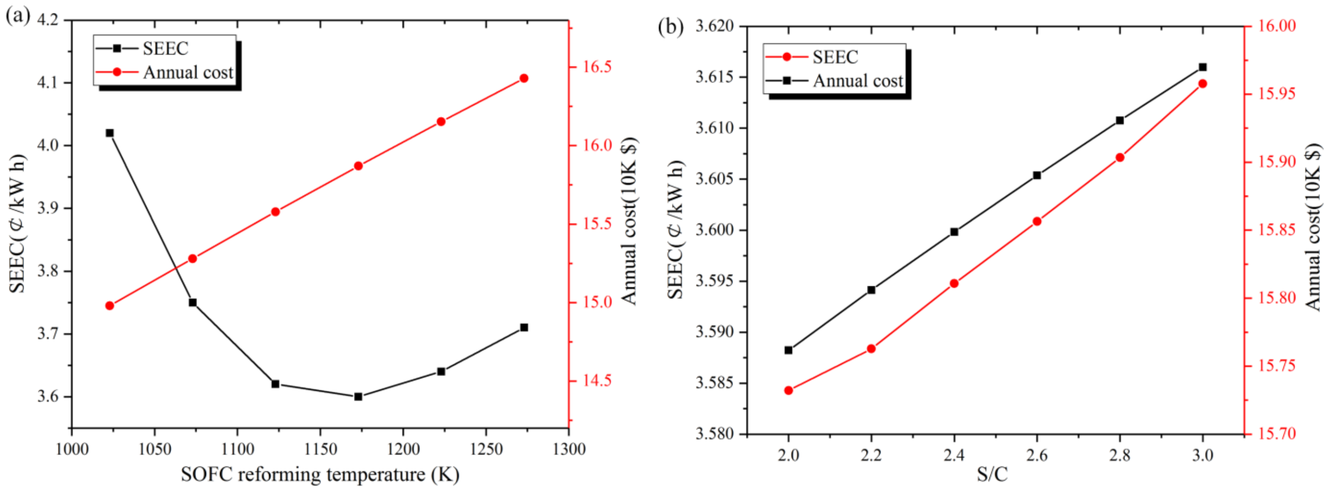

Fig. 4 The effects of SOFC reforming temperature and S/C ratio on the SEEC of the hybrid system (a) SOFC reforming temperature; (b) S/C ratio.

corresponding components gradually increases, which result in an increase in capital cost. Therefore, the annual cost of the system is gradually inflation. However, before the reforming temperature is 1173 K, the increase of SOFC reforming temperature makes the system output power increase more than the capital cost of system components, so the SEEC of this hybrid system gradually decreases. After the SOFC reforming temperature is 1173 K, the situation is just the opposite, the SEEC gradually increased. From the perspective of reducing SEEC, 1173 K is the optimal SOFC reforming temperature. Fig. 4b displays the effect of the S/C ratio on the SEEC of the hybrid system. It is found that the effect of S/C ratio is much smaller than that of the SOFC reforming temperature. The SEEC increase from 3.584 to 3.614 ¢/kW h, only 0.8% variation at most when the S/C ratio increased from 2.0 to 3.0. Also the S/C ratio has little effect on annual cost.

Fig. 5a displays the influence of fuel utilization on the SEEC and annual cost of the hybrid system. The SEEC reduce from 3.864 to 3.445 ¢/kW h and the annual cost increase from 15.73 k$ to 15.94 k$ as the fuel utilization rise from 0.6 to 0.85. In this work, fuel utilization is defined as the ratio of fuel utilized by SOFC to fuel input. Since SOFC is the dominant power generation in the hybrid system while the HCCI engine is auxiliary, the increase of fuel utilization means the increase of system output power, so the capital cost and annual cost of the system will increase correspondingly. However, the impact of increased output power on the SEEC is greater than that of increased annual costs, so the SEEC decreases as fuel utilization increases. Fig. 5b further reveals the thermo-economic performance of the hybrid system under different NG price. When the NG price changes from 0.062 to 0.186 $/Nm^3, the annual operation cost is increased from 4.38 to 13.14 k$.

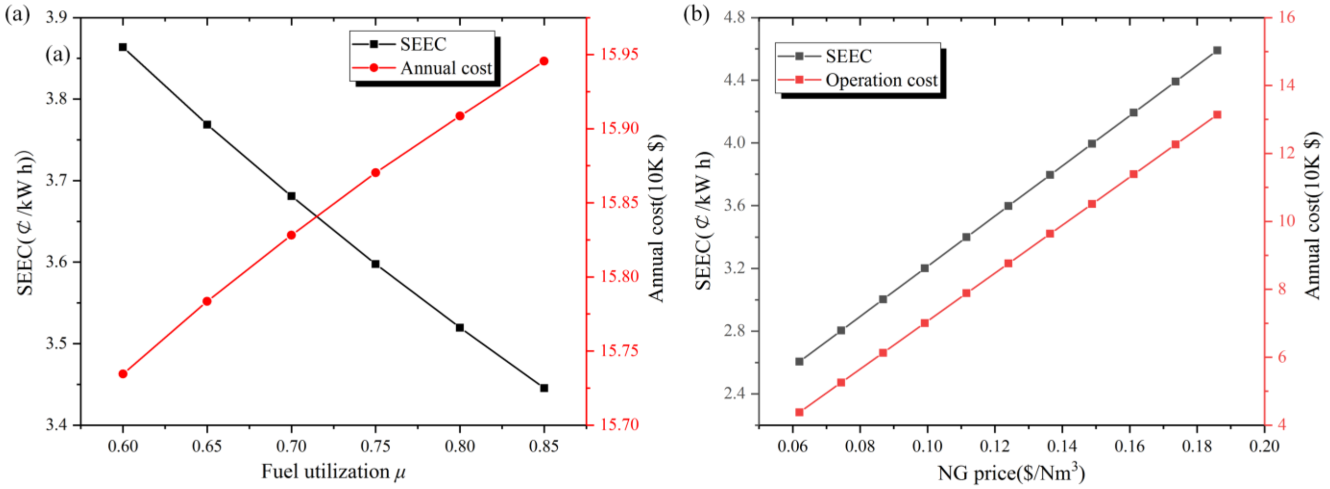

Fig. 5 The effects of fuel utilization and NG price on the SEEC of the hybrid system (a) fuel utilization; (b) NG price.

Accordingly, the SEEC is increased from 2.60 to 4.59 ₵/kW h with the fluctuation of about 76.5%. Both the annual operation cost and the SEEC linearly increase with the increase of the NG price.

4. CONCLUSION

This work proposed a novel NG-fueled SOFC-HCCI engine hybrid energy conversion system as distributed power plant with high efficiency and developed the thermo-economic model of the system based on the previously established thermodynamic model. Then the thermo-economic parametric analysis are investigated to optimize the thermo-economic performance. The results showed that the specific electric energy cost of the hybrid system is calculated to be 3.75 ₵/kW h, which has a significant decrease compared to the energy cost (5.46 ₵/kW h) of a standard power plant. Moreover, the payback period of this system is approximately 6.8 years and the annual return on investment is 4.6%. The comparison confirms that the proposed SOFC-HCCI engine hybrid system is economically feasible as the distributed power plant in the practical applications.

ACKNOWLEDGEMENT

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