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Performance Analysis of a Direct Carbon Fuel Cell Cogeneration System Combined with a Two-Stage Thermoelectric Generator

Jiahui Liu¹, Houcheng Zhang ^{1,*}, Jiatang Wang², Jiapei Zhao², Fu Wang², He Miao², Jinliang Yuan², Shujin Hou ^{3,*}

¹ Department of Microelectronic Science and Engineering, Ningbo University, Ningbo 315211, China

² Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, China

³ College of Physics and Electronic Engineering, Nanyang Normal University, Nanyang 473061, China

*E-mail: <u>zhanghoucheng@nbu.edu.cn</u> (H. Zhang), <u>houshujingrb@163.com</u> (S. Hou).

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A new cogeneration system model consisting of a DCFC (direct carbon fuel cell), a TTEG (two-stage thermoelectric generator) and a regenerator is proposed, where the DCFC directly and efficiently converts the chemical energy of carbon into electricity and waste heat, and the TTEG harvests the waste heat for additional electricity production. For a given heat flow rate, the TTEG is optimized using maximum power output as an objective function. An analytic relationship between the operating current density of DCFC and the dimensionless electric current of optimized TTEG is derived. The mathematical formulas for the power output and efficiency of the cogeneration system are specified under different operating conditions. The proposed hybrid system is found to be more efficient than the sole DCFC and DCFC-TEG hybrid system. It is found that the maximum attainable power density allows about 50% larger than that of the stand-alone DCFC. Furthermore, the effects of operating current density, operating temperature, heat conductivity, number of thermocouples, figure of merit of the thermoelectric materials and DCFC anode dimension on the cogeneration system performance are discussed in detail.

Keywords: Direct carbon fuel cell; Two-stage thermoelectric generator; Cogeneration system; Performance analysis; Parametric study

1. INTRODUCTION

In view of the worldwide growing demand for electrical energy and rapid consumption of fossil fuels, numerous funds and efforts have been devoted into developing fuel cells, which can directly convert the chemical energy of a fuel into electricity through electrochemical reactions [1, 2]. Among

various types of fuel cells, direct carbon fuel cells (DCFCs) have a unique feature that can directly use coal, coke, and petroleum coke as well as biomass carbon as both fuel and electrode without gasification [3-8]. In contrast to other kinds of fuel cells, DCFCs have the following advantages [9-15]: (1) Fuel sources are broad, especially including the abundant and cheap coal; (2) The theoretical electrochemical conversion efficiency is high (close to 100%); (3) The nearly pure CO₂ can be easily collected for downstream disposal.

DCFCs, working at a high temperature (above 600° C), generate a lot of high-grade waste heat due to the irreversible losses in the electrochemical reactions [13-16]. At present, the low power density is an important obstacle that hinders the commercial use of DCFCs. To improve the power density, considerable investigations have focused on various aspects, including high performance electrolytes and catalysts fabrication, novel structure designs, fuel oxidation mechanisms and materials issues [17-19]. What's more, the equivalent power density of DCFCs can be further improved at the system level by recovering the waste heat for additional power generation [20-22]. For instance, Yang et al. [21] put forward a cogeneration system integrating the thermophotovoltaic cell to a DCFC for efficiently exploiting the waste heat, and the results showed that the maximum power output density of the cogeneration system could attain 734.7 W m⁻², which was more than 2 times of that of a sole DCFC. In order to further convert the waste heat of the DCFC for power generation, Chen et al. [22] established the hybrid system mainly consists of a DCFC with molten carbonate as electrolyte, a regenerator and a Carnot heat engine and proved that the performance of the DCFC could be greatly enhanced by connecting a Carnot heat engine.

TEGs (thermoelectric generators) are semiconductor systems which can directly convert thermal energy into electricity based on the Seebeck effect [23]. Compared with conventional power generation systems, TEGs offers many advantages such as no vibration, silence, modularity, higher reliability and environmental friendliness [24,25]. TEGs have been widely used as a waste heat recovery technology for energy saving and emission reduction [23,26]. To overcome the poor performance, a number of studies have been conducted on thermoelectric materials to improve the physical properties such as the Seebeck coefficient, thermal conductivity, electrical conductivity and thermal stability [27-29]. Alternatively, the performance of TEGs can be also improved by recovering the rejected waste heat for additional power generation through adding another stage TEGs. The two-stage TEGs (TTEGs) show advantages in waste heat recovery under the big temperature difference conditions and have attracted many interests [30-37]. For example, Cheng et al. [33] developed a TTEG model and a single-stage TEG model to predict and compare the power generation performance on hypersonic vehicles at different heating channel inlet temperatures. Their results showed that the TTEG had a greater potential on performance enhancement for hypersonic vehicles. Liu et al. [34] proposed a novel prototype TTEG for vehicle exhaust heat recovery. The TTEG thermal efficiency was improved by 32% compared to that of the single stage TEG under the same operating conditions. Sun et al. [36] compared the TTEG and the traditional single-stage TEG for waste heat recovery from the high-temperature exhaust gas of internal combustion engine. They found that the maximum values of output power, conversion efficiency and exergy efficiency of a TTEG at 800 K were 10.9%, 12.4% and 12.5% higher than those of the singlestage TEG, respectively. Furthermore, Cheng et al.[37] compared the performance of the single- and multi-stage TEGs under a larger temperature difference condition. They found that the multi-stage TEGs

had significant advantages over single-stage TEG when the temperature difference was over 500 K. Recently, Zhao et al. [38] used a single-stage TEG to recover the waste heat in a DCFC and found that the equivalent maximum power density of the proposed system allowed 50% larger than that of the sole DCFC system. Obviously, TTEGs are expected to perform better as the waste heat recovery technology for DCFCs compared to the single-stage TEGs. However, no study has been reported on this topic yet.

In this paper, a new combined system that uses a TTEG to harvest the waste heat from a DCFC is proposed. The amount of available waste heat from the DCFC will be calculated by considering the overpotential losses in the DCFC, regenerative loss in the regenerator and heat leak loss from the DCFC to the surroundings. The number of thermoelectric elements amount the toping stage and the bottoming stage will be optimized to maximize the power out of the TTEG. The mathematic expressions for power output and efficiency of the combined system are derived by considering the contributions from both DCFC and TTEG. Performance comparisons between the single-stage TEG and the two-stage TEG as the waste heat recovery technologies will be performed, and the problem whether TTEG is better or worse than the single-stage TEG will be solved. Furthermore, various parametric studies are carried out to examine the dependence of the proposed system performance on some operating conditions and designing parameters.



2. SYSTEM DESCRIPTION

Figure 1. The schematic diagram of a cogeneration system consisting of a DCFC and a two-stage thermoelectric generator.

The proposed system consists of a DCFC, a TTEG and a generator, as shown in Fig. 1. The DCFC converts the fuel chemical energy into electrical power P_{DCFC} and high-grade waste heat. The TTEG directly converts a part of the waste heat, Q_1 , from the DCFC at the temperature T into electric power P_{TTEG} and then rejects heat, Q_2 , into the environment at the temperature T_L . The regenerator acts

as a heat exchanger that heats the reactants with the help of the exhaust gases. Another part of the waste heat produced in the DCFC, Q_L , is directly leaked into the environment due to the big temperature difference. The rest part of the waste heat, Q_R , is transferred to compensate the regenerative losses in the regenerator.

To analyze the proposed hybrid system performance, the following major assumptions are adopted [19, 38-40]:

- (1) Both DCFC and TTEG are operated under steady-state conditions;
- (2) Geometric configuration of the TTEG is in the optimum form;
- (3) Operating temperature and pressure are uniform and invariant in the DCFC;
- (4) No reactant is left after the electrochemical reactions;
- (5) All gases involved are assumed to be compressible ideal gases;
- (6) Carbon fuel is regarded as a rigid sphere and packed with a simple hexagonal pattern;
- (7) Carbon fuel is assumed to be completely oxidized by electrochemical reactions;
- (8) Heat leakage from the TTEG to the surroundings is neglected;

(9) External heat-transfer irreversibilities between the TTEG and the heat sources are neglected.

In view of the above assumptions, we will take every factor in the hybrid system into account, and then fully investigate the performance characteristics of the hybrid system.

2.1. The DCFC

The DCFC, mainly composed of a packed bed anode and a lithium doped NiO cathode with Li_2CO_3/K_2CO_3 eutectic melt as an electrolyte sandwiched between the two electrodes, directly converts the chemical energy of the incoming graphite into electricity and waste heat [17, 38]. The overall reaction is: $C+O_2 \rightarrow CO_2 + Electricity + Heat$. The performance of the DCFC can be well predicted by an analytic method. As described in Ref. [38,39], the mathematic expression of the cell output voltage, V, can be given by taking the activation, ohmic and concentration overpotential losses as the main reasons of voltage reduction:

$$V = E - V_{act,an} - V_{act,cat} - V_{con} - V_{ohm},$$
⁽¹⁾

where

$$E = E_0 + \frac{RT}{n_e F} \ln \left[\frac{p_{\text{O}_2, \text{ cat}} \left(p_{\text{CO}_2, \text{ cat}} \right)^2}{p_{\text{CO}_2, \text{ an}}} \right],$$
(2)

$$V_{act,an} = \frac{RT}{2F} \ln \left[\frac{j}{2j_{0,an}} + \sqrt{\left(\frac{j}{2j_{0,an}}\right)^2 + 1} \right],$$
(3)

$$V_{act,cat} = \frac{RT}{2F} \ln\left[\frac{j}{2j_{0,cat}} + \sqrt{\left(\frac{j}{2j_{0,cat}}\right)^2 + 1}\right],\tag{4}$$

$$V_{con} = \frac{RT}{n_e F} \ln\left(\frac{j_{\rm lim}}{j_{\rm lim} - j}\right),\tag{5}$$

and

$$V_{ohm} = \sum I_{c,i} R_{c,i} + \sum I_{e,i} R_{e,i} + V_{ec} , \qquad (6)$$

E is the equilibrium potential; $E_0 = -\Delta g^0(T)/(n_e F)$ and $\Delta g^0(T)$ are, respectively, the standard potential and the Gibbs free energy change at the standard pressure (1 atm) and temperature *T*; n_e is the number of electrons involved per reaction; *F* is the Faraday's constant; *R* is the universal gas constant; p_{O_2} and p_{CO_2} are, respectively, the partial pressures of O_2 and CO_2 at the electrode surfaces; the subscripts "an" and "cat" represent anode and cathode, respectively; *j* is the current density flowing through the cell; $V_{act,an}$ and $V_{act,cat}$ are, respectively, the anode and cathode activation overpotentials; $j_{0,an} = K_B \exp(-E_B/T)$ and $j_{0,cat} = j_{0,cat}^0 (p_{CO_2,cat})^{r_1} (p_{O_2,cat})^{r_2}$ are, respectively, the anode and the cathode exchange current densities; V_{con} is the concentration overpotential, $j_{iim} = n_e F K_{CO_2} C_{CO_2}^b$ is the limiting current density, K_{CO_2} is the mass transportation coefficient of CO₂, and $I_{e,i}$ are, respectively, the electric currents flowing through the carbon phase and electrolyte phase at the *i*th slab in the anode, $R_{c,i}$ and $R_{e,i}$ are, respectively, the corresponding resistances in the carbon phase and electrolyte, V_{ec} is the total ohmic overpotential losses in the electrolyte and the cathode [17, 38].

Considering all the irreversible losses abovementioned, the power output P_{DCFC} and the efficiency η_{DCFC} of the DCFC can be, respectively, expressed as [39, 40]:

$$P_{DCFC} = VI = VjA, \tag{7}$$

and

$$\eta_{DCFC} = \frac{P_{DCFC}}{-\Delta H} = -\frac{n_e FV}{\Delta h},\tag{8}$$

where *l* is the electric current flowing through the cell; *A* is the polar plate area of the DCFC; $-\Delta H$ is the total energy released per unit time, $(-\Delta h)$ is the molar enthalpy change of the electrochemical reaction in the fuel cell 39.

2.2. The regenerator

The regenerator in the hybrid system works as a heat exchanger, which preheats the incoming reactants from ambient temperature to the operating temperature of the DCFC by absorbing the high-temperature heat contained in the products. The regenerative loss is usually given by [42]:

$$Q_{R} = \alpha_{re} A_{re} \left(1 - \varepsilon \right) \left(T - T_{L} \right), \tag{9}$$

where α_{re} and A_{re} are, respectively, the heat-transfer coefficient and the heat-transfer area of the regenerator, and \mathcal{E} is the effectiveness of the regenerator.

2.3. The TTEG

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Fig.1. gives a schematic diagram of the TTEG. The TTEG consists of multiple pairs of thermocouples, in which the top stage has *m* pairs of thermocouples and the bottom stage has *n* pairs of thermocouples. Each thermocouple is composed of an N-type and a P-type semiconductor legs. All thermocouples are connected in series, so that the electric current I_g flowing through all thermocouples in the TTEG is the same [36, 40]. A barrier must be sandwiched in between the two stages, and the thermal conductivity of the barrier should be as good as possible so that the temperature at the bottom of the top stage and the temperature at the top of the bottom stage can be regarded to be the same, i.e., T_m . Q_1 is the heat flow from the DCFC to the TTEG, Q_m is the heat-transfer rate between the two stages of TEGs, and Q_2 is the heat flow from the TTEG to the environment. Neglecting the Thomson effect and assuming the heat transfers obey Newton's law, Q_1 , Q_m and Q_2 can be, respectively, expressed as [34, 36]:

$$Q_{1} = \alpha m I_{g} T - 0.5 m I_{g}^{2} R_{g} + m K_{g} \left(T - T_{m} \right), \tag{10}$$

$$Q_m = \alpha m I_g T_m + 0.5 m I_g^2 R_g + m K_g \left(T - T_m \right), \tag{11}$$

$$Q_m = \alpha n I_g T_m - 0.5 n I_g^2 R_g + n K_g \left(T_m - T_L \right), \tag{12}$$

and

$$Q_{2} = \alpha n I_{g} T + 0.5 n I_{g}^{2} R_{g} + n K_{g} \left(T_{m} - T_{L} \right),$$
(13)

where $\alpha = \alpha_N + \alpha_P$, α_N and α_P are, respectively, the Seebeck coefficients for a thermocouple an N-type semiconductor leg and a P-type semiconductor leg, K_g is the thermal conductance of a thermocouple, and R_g is the internal electrical resistance of a thermocouple [37, 41].

Eliminating T_m , Eqs. (10) - (13) yield:

$$q_{1} = \frac{Q_{1}}{K_{g}T} = \frac{mi - \frac{m}{2ZT}i^{2} + m + \left[\frac{m+n}{2ZT}i^{2} + m + \frac{n}{\theta}\right]m}{\left[(m-n)i - (m+n)\right]},$$
(14)

and

$$q_{2} = \frac{Q_{2}}{K_{g}T_{L}} = \frac{ni + \frac{n}{2ZT_{L}}i^{2} - n - \left\lfloor \frac{m+n}{2ZT_{L}}i^{2} + m\theta + n \right\rfloor n}{\left[(m-n)i - (m+n) \right]},$$
(15)

where $ZT_L = \alpha^2 / K_g R_g$ is the figure of merit of a thermocouple, $i = \alpha I_g / K_g$ is the dimensionless electric current, and $\theta = T/T_L$ is the temperature ratio between T and T_L .

The power output P_{TTEG} and efficiency η_{TTEG} of the TTEG can be expressed as:

$$P_{TTEG} = Q_1 - Q_2 = K_g T_L n(\chi + 1) \left[\frac{(\chi \theta - 1)i}{\chi + 1} - \frac{i^2}{2ZT_L} + \frac{\chi \theta + 1}{\chi + 1} + \frac{(\chi + 1)i^2 / (2ZT_L) + (\chi \theta + 1)}{(\chi - 1)i - (\chi + 1)} \right], (16)$$

and

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$$\eta_{TTEG} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{b_1 + b_2 i + b_3 i^2 + b_4 i^3}{b_1 + b_5 i + b_6 i^2 + b_7 i^3},$$
(17)

where $\chi = m/n$ is the ratio of thermocouple numbers between the top stage and the bottom stage, $b_1 = (1-\theta)\chi$, $b_2 = -2\chi$, $b_3 = \chi - 1 - (1+\chi)/(ZT_L)$, $b_4 = (\chi - 1)/(2ZT_L)$, $b_5 = -2\chi\theta$, $b_6 = \chi(\chi - 1)\theta + [\chi(1+\chi)]/(ZT_L)$, and $b_7 = -\chi(\chi - 1)/(2ZT_L)$.

The power output of TTEG can be maximized by optimizing the ratio χ . Based on Eq. (16) and the extreme conditions $\partial P_{TTEG}/\partial \chi = 0$, one has

$$\chi_{opt} = \frac{i^3 - (2d_1 - 1)i^2 - 2d_1i + 2\sqrt{i\left[-i^4 + 2d_1i^3 - d_2i^2 + d_3i + 2d_1d_4\right]}}{i(i-1)(i-2d_1)},$$
(18)

where $d_1 = \theta ZT_L + 1$, $d_2 = ZT_L(\theta + 1)$, $d_3 = ZT_L(2\theta^2 ZT_L + 2\theta ZT_L + \theta + 3)$, $d_4 = ZT_L(\theta - 1)$. Substituting Eq. (18) into Eqs. (16) and (17), we can obtain the maximum power output $P_{TTEG,max}$ and its corresponding efficiency $\eta_{TTEG,max}$

$$P_{TTEG,\max} = K_g T_L n \Big(\chi_{opt} + 1 \Big) \left[\frac{\left(\chi_{opt} \theta - 1 \right) i}{\chi_{opt} + 1} - \frac{i^2}{2ZT_L} + \frac{\chi_{opt} \theta + 1}{\chi_{opt} + 1} + \frac{\left(\chi_{opt} + 1 \right) i^2 / (2ZT_L) + \left(\chi_{opt} \theta + 1 \right)}{\left(\chi_{opt} - 1 \right) i - \left(\chi_{opt} + 1 \right)} \right], \quad (19)$$

and

$$\eta_{TTEG,\max} = 1 - \frac{f_1 + f_2 i + f_3 i^2 + f_4 i^3}{f_1 + f_5 i + f_6 i^2 + f_7 i^3},$$
(20)

where
$$f_1 = (1-\theta)\chi_{opt}$$
, $f_2 = -2\chi_{opt}$, $f_3 = \chi_{opt} - 1 - (1+\chi_{opt})/(ZT_L)$, $f_4 = (\chi_{opt} - 1)/(2ZT_L)$,
 $f_5 = -2\theta\chi_{opt}$, $f_6 = \chi_{opt}(\chi_{opt} - 1)\theta + [\chi_{opt}(1+\chi_{opt})]/(ZT_L)$, and $f_7 = -\chi_{opt}(\chi_{opt} - 1)/(2ZT_L)$.

2.4. The performance of the hybrid system

The part of the waste heat leaked from the DCFC to the environment, Q_L , can be described by

[43]

$$Q_L = K_L A_L (T - T_L), \qquad (21)$$

where K_L is heat transfer coefficient, and A_L is the corresponding heat transfer area.

According to the first law of thermodynamics, the part of the waste heat transferred to the TTEG, Q_1 , can be calculated as [42, 43]

$$Q_{1} = -\Delta \dot{H} - P_{DCFC} - Q_{R} - Q_{L} = -\frac{A\Delta h}{2F} \left[\left(1 - \eta_{DCFC} \right) j - \frac{2Fc_{1} \left(T - T_{L} \right)}{-\Delta h} - \frac{2Fc_{2} \left(T - T_{L} \right)}{-\Delta h} \right], \quad (22)$$

where $c_1 = K_{re}A_{re}(1-\varepsilon)/A$ and $c_2 = K_LA_L/A$ are two temperature-independent composite constants which are relative to the regenerative losses and heat leak losses, respectively.

Considering the heat leak within the TTEG, the TTEG begins to generate electricity only when the following requirement is satisfied [38, 41]:

$$-\Delta H - P_{DCFC} > Q_R + Q_L + mK_g \left(T - T_m\right).$$
⁽²³⁾

Substituting Eqs. (7), (9), (21) and (22) into Eq. (23), we have

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$$j > j_B = \left[\frac{2F}{-\Delta h \left(1 - \eta_{DCFC}\right)}\right] \left[\left(c_1 + c_2\right) \left(T - T_L\right) + n \chi_{opt} K_g \left(T - T_m\right) / A\right],$$
(24)

where j_B is the lower bound of operating current density from which the TTEG starts to work. Based on Eqs. (16) - (22), one may also easily obtain the upper bound of j, j_M , from which the TTEG stops working. Thus, the effective operating current density of DCFC that allows the TTEG to work is given by $j_B < j < j_M$ and the effective operating current density interval is given by $\Delta j = j_M - j_B$.

When the TTEG is operated in the region of $j_B < j < j_M$, the mathematical relationship between *i* and *j* is given by

$$\chi_{opt}i - \frac{\chi_{opt}i^{2}}{2ZT} + \chi_{opt} + \frac{\left(\frac{\chi_{opt}+1}{2ZT}i^{2} + \chi_{opt} + 1/\theta\right)\chi_{opt}}{\left[\left(\chi_{opt}-1\right)i - \left(\chi_{opt}+1\right)\right]} = \frac{-A\Delta h}{2FnK_{g}T}\left[(1 - \eta_{DCFC})j - \frac{2Fc_{1}\left(T - T_{L}\right)}{-\Delta h} - \frac{2Fc_{2}\left(T - T_{L}\right)}{-\Delta h}\right].$$
(25)

Considering the contribution of the power output-oriented optimized TTEG, the equivalent power output *P* and efficiency η for the hybrid system can be, respectively, given by [41, 43]

$$P = \begin{cases} = P_{DCFC} + P_{TTEG, \max} & (j_B < j < j_M) \\ = P_{DCFC} & (j \le j_B \text{ or } j \ge j_M) \end{cases}$$
(26)

and

$$\eta = \begin{cases} = \frac{P_{DCFC} + P_{TTEG, \max}}{\bullet} & (j_B < j < j_M) \\ = \eta_{DCFC} & (j \le j_B \text{ or } j \ge j_M) \end{cases}$$
(27)

3. RESULTS AND DISCUSSION

Fig. 2 compares the power density and the efficiency of the DCFC, TTEG and proposed hybrid system, where $P_{DCFC}^* = P_{DCFC} / A$, $P_{TTEG}^* = P_{TTEG} / A$, $P^* = P / A$ are, respectively, the corresponding power densities, $P_{DCFC,\text{max}}^*$, $P_{TTEG,\text{max}}^*$ and P_{max}^* are, respectively, the maximum achievable power densities for the DCFC, TTEG and hybrid system. It is seen from Fig. 2 (a) that P_{DCFC}^* , P_{TTEG}^* and P^* first increase and then decrease with increasing j, and the TTEG only works in the region of $j_B < j < j_M$. Fig. 2 (b) indicates that η_{DCFC} ongoingly decreases with an increase in j, but η_{TTEG} first increases to attain its peak value $\eta_{TTEG,\text{max}}$ and then decreases. As a consequence, η somewhat increases from j_B and then decreases in the region of $j_B < j < j_M$. Outside of the region of $j_B < j < j_M$, the curves of $P^* \sim j$ and $\eta \sim j$ are overlapped with the curves of $P_{DCFC}^* \sim j$ and $\eta_{DCFC} \sim j$, respectively. It also shows that the operating current density at P_{max}^* is always different from that at $P_{DCFC,\text{max}}^*$.



Figure 2. The curve of (a) power densities and (b) efficiencies varying with the operating current density of DCFC, where $P_{DCFC}^* = P_{DCFC} / A$, $P_{TTEG}^* = P_{TTEG} / A$ and $P^* = P / A$ are, respectively, the power densities for the DCFC, TTEG and proposed system, $P_{DCFC,max}^*$, $P_{TTEG,max}^*$ and P_{max}^* are, respectively, the corresponding maximum achievable power densities, η_P and j_P are, respectively, the efficiency and operating current density of the proposed system at P_{max}^* , j_B and j_M are, respectively, the lower bound and upper bound current densities between which the TTEG enables to work, j_S is the stagnation current density from which the DCFC does not deliver electricity any more.

 Table 1. Parameters used in the modeling 38.

Parameter	Value
Faraday constant, F (C mol ⁻¹)	96,485
Number of electrons, n_e	4
Universal gas constant, R (J mol ⁻¹ K ⁻¹)	8.314
Operating pressure, $P(atm)$	1.0
Height of packed bed anode, $H(m)$	0.001
Diameter of spherical graphite particle, D_C (m)	1.0*10 ⁻⁵ 17
Concentration independent cathode exchange current density, $j_{0,cat}^0$ (A m ⁻²)	500 17
Bulk gas compositions at the cathode side	33%O ₂ /67%CO ₂ 17
Pre-exponential factor of the backward reaction, K_B (A m ⁻²)	5.8*10 ⁹ 38
Temperature activation of the backward reaction, $E_B(K^{-1})$	22175
Mass transport coefficient of CO_2, K_{CO_2} (m s ⁻¹)	3.5*10 ⁻²
Constant r_1	-1.250
Constant r_2	0.375
Polar plate area of the DCFC, A (m ²)	0.04
Operating temperature of the DCFC, $T(K)$	923
Temperature of the environment, $T_L(K)$	298.15
Figure of merit of the thermoelectric materials, ZT_L	1.0 38
Heat conductivity of a thermoelectric element, K_g (W K ⁻¹ m ⁻¹)	0.01 41
Number of TEGs in the second stage, n	5
Constant c_1 or c_2 (W K ⁻¹ m ⁻²)	0.1

For the parameters given in Table 1, the hybrid system reaches its maximum power density at about 702.86 Am⁻², and the DCFC and TTEG reach their maximum power densities at about 667.08 Am⁻² and 721.25 Am⁻², respectively. Meanwhile, the maximum power density of the hybrid system can reach 321.21 Wm⁻², and the maximum power density of DCFC is equal to 211.02 Wm⁻². When *j* is operated in the region of $j_B < j < j_M$, the power density and efficiency of the hybrid system are obviously larger

than that of the DCFC. It is clearly implied that the performance of the DCFC can be effectively enhanced by coupling a TTEG for further recycling the waste heat into electricity.



Figure 3. Performance comparisons between two-stage TEG with single-stage TEG as the bottoming waste heat recovery technologies for DCFCs.



Figure 4. The effects of operating temperature T on the cogeneration system performance.



Figure 5. The effects of the heat conductivity K_{g} on the cogeneration system performance.

Numerical calculations further show that P_{\max}^* is about 52.21% larger than $P_{DCFC,\max}^*$, and the efficiency of the hybrid system at its maximum power density is about 51.73% larger than that of the sole DCFC at its maximum power density. It shows that the increase in the power density is more obvious than that in the efficiency. Fig. 2 also shows that when j is larger than j_p , a continuously increase in j not only lowers η but also lowers P^* . Taking both η and P^* into consideration simultaneously, the optimum operation region of j is located in $j_B < j < j_p$.

Fig. 3 presents the performance comparisons between the TTEG and the single-stage TEG as the bottoming waste heat recovery technologies for DCFCs, where the numbers of thermocouples used in TTEG and the single-stage TEG are the same. It is evidently observed that the maximum power density of the TTEG hybridized system is larger than that of the single-stage TEG hybridized system in Ref. [38], the values of j_B and j_M of former are different from that of the latter, and the value j_P of the former is also different from that of the latter. Outside the region of $j_B < j < j_M$, the performances of these two hybridized systems are the same as that of the stand-alone DCFC. Compared to the single-stage TEG, the TTEG can involve in the additional electricity generation at a smaller j. Thus, TTEG is more suitable as the waste heat recovery technology for DCFCs.

Fig. 4 illustrates the DCFC operating temperature *T* affects the performance of the proposed system. It is showed that both P^* and η increase with the increasing operating temperature, and the effects of *T* become stronger at a larger *T*. This is because a higher working temperature leads to more efficient ionic conductivity in the electrolyte and a lower ohmic overpotential. Moreover, a large temperature difference also benefits the performance of TTEG [44]. When *j* is in the region of $j \le j_B$

or $j \ge j_M$, the efficiency and power density of the proposed system are the same as that of the sole DCFC. In addition, a greater operating temperature *T* leads to a larger j_B , j_M , and j_P , while the effective operating current density interval Δj is also increased as *T* increases. However, a high temperature would cause some problems such as higher costs, and longer start-up and shutdown times[45].

It is seen from Fig. 5, that the curves of $P^* \sim j$ and $\eta \sim j$ coincide with that of the $P_{DCFC}^* \sim j$ and $\eta_{DCFC} \sim j$, respectively. In the region of $j_B < j < j_M$, P_{max}^* increases with the increasing K_g , and simultaneously, j_P , j_B , j_M and Δj also increase as K_g increases, while the value of j_S keeps as an invariant. Fig. 5 shows that the effects of K_g become greater as j increases. For the typical parameters given in Table 1, the K_g should be designed as larger as possible. Meanwhile, a larger K_g is always beneficial for the performance improvement of TTEG, but a larger K_g often leads to higher manufacturing cost.



Figure 6. The effect of the number of thermocouples n on the cogeneration system performance.



Figure 7. The effect of figure of merit thermoelectric material ZT_L on the cogeneration system performance.



Figure 8. The effect of the anode dimension on the cogeneration system performance

Fig. 6 shows the number of thermocouples n affects the performance of the proposed system. It is seen that the maximum attainable power density P_{\max}^* increases with the increasing n as more thermocouples engage in the electricity generation. Meanwhile, j_B , j_M , j_P and Δj shift to larger ones with an increase in j. Fig. 6 also indicates that the effects of n on the proposed system performance become more pronounced as j increases. In practice, the number of thermocouples should be as large as possible, and the thermocouples are suggested to be cascaded into the multi-stage form.

The figure of merit of the thermoelectric materials ZT_L significantly impacts the TTEG performance and thus impacts the proposed system performance [46]. As shown in Fig. 7, both P^* and η are increased with the increasing ZT_L in the region of $j_B < j < j_M$, and P^*_{max} , j_B and j_P shift to larger ones as ZT_L increases, while j_M and j_S keep invariant, and consequently, Δj decreases with the increasing ZT_L . It can be observed that the higher value of the ZT_L will cause a better performance of the system. Up to now, thermoelectric materials with a value of ZT_L exceeding 2.4 have been already reported [47].

Fig. 8 describes the DCFC anode dimension N_s affects the proposed system performance. It is observed that both P^* and η increase as N_s drops, and P^*_{max} , j_B , j_P , j_M , Δj and j_s shift to larger ones with a decrease in N_s . With an increase in j, η continuously decreases, while P^* first increases to attain P^*_{max} and then decreases to zero at j_s . Moreover, the effects of anode dimension on the proposed system performance become more prominent as j increases. A smaller anode dimension enhances the ionic conductivity and reduces ohmic overpotential of the DCFC, and consequently, the hybrid system performance is better when the anode dimension is smaller.

4. CONCLUSIONS

A novel cogeneration system mainly consisting of a DCFC, a regenerator and a TTEG is proposed to recover the waste heat generated in the DCFC for additional power generation. Considering multiple irreversible losses within the system, analytic expressions evaluating the performance of the DCFC, TTEG and cogeneration system are derived. The relation between the DCFC operating electric current and the TTEG electric current is given. The power output and efficiency of the cogeneration system are specified under different operating conditions. Compared with the single-stage TEG, the TTEG is found to be effective and advantageous as the waste heat recovery technology for DCFCs. In addition, comprehensive parametric studies are conducted to examine the dependence of the proposed system performance on some designing parameters and operating conditions such as operating current density, operating temperature, number of thermocouples, thermal conductance of a thermocouple, figure of merit of thermoelectric materials and anode dimension. The results obtained may provide some theoretical bases for the DCFC performance improvement through cogeneration approach.

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