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Short Communication

A Study of Direct Carbon Fuel Cell/Heat-Driven Refrigerator Coupled System

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This paper presents a general framework of coupled power system composed of heat driven refrigerator and direct carbon fuel cell (DCFC). Based on the three heat source refrigerator and DCFCs pattern, the efficiency and equivalent power output of the coupled system are obtained. By numerical calculation, some expressive curves of the coupled system are analyzed. The conclusions show that the performance of the coupled system of DCFC/heat driven refrigerator is stronger than that of single fuel cell during the operating interval.

Keywords: Coupled system; DCFC; Heat-driven refrigerator; Performance analysis

1. INTRODUCTION

Among all the possible fuel cell energy sources, hydrogen is often the preferred fuel cell energy source with its high power density. However, the production, storage and transportation of hydrogen have been huge problems. Carbon has obvious advantages in storage and transportation compared with the prevailing hydrogen fuel. DCFCs get their name from the fact that they can use carbon immediately as a fuel. There is no need to gasify the fuel in the process of converting chemical energy into electricity, or to use large moving machines like conventional generators [1-4]. Virtually total the carbon-rich materials, such as oil, coal and natural gas, can be breezily modified or depurative into the fuel of DCFCs. Therefore, DCFCs are considered as an attractive solution in the power generation industry [5-8].

In general, the operating temperature range of DCFCs is 973~1073K [6, 9, 10], and a considerable portion of the squandering heat generated from DCFC can be reused. The high temperature offers the possibility of regenerating power from the squandering heat. Therefore, how to utilize the squandering heat generated by DCFC is very worthy of further study. In order to improve the overall performance of fuel cells [11-15], a great deal of researches has been done on the coupled systems of high temperature fuel cells (such as solid oxide fuel cells and molten carbonate fuel cells). However, there are few researches on DCFC/heat driven refrigerator, and most of the studies are focused on the arrangement of coupled electrode structure [16].

In this article, we will build a new coupled system, with a heat-driven refrigerator, a DCFC and a regenerator, using the squandering heat generated by DCFC. On this basis, the expressions of power output and efficiency are obtained. Meanwhile, the general characteristics of the coupled system are displayed by numerical calculation. Finally, some important results are drawn.

2. THE DCFC

The pattern of DCFC presented in this paper has been previously studied in Ref. [17]. DCFC converts the chemical energy in the carbon fuel into electric energy. The whole chemical reaction equation is as follows: $\mathrm{C}+\mathrm{O}_2 \rightarrow \mathrm{CO}_2 + Electricity + Heat$. The DCFC is composed of a porous cathode, an encased bed anode and a fusional carbonate electrolyte which is mezzanine between the two electrodes. The essential thermodynamic relationship of total reaction in DCFC can be given by the following formula [7, 8, 17]

$$-\Delta\dot{H} = -\frac{\Delta h}{n_e F} I, \qquad (1)$$

where $(-\Delta h)$ is the molar enthalpy variability which can be obtained from the data supply in Ref. [17], I is the operating electric current of the DCFC, n_e is the quantity of mole electrons metastasized per mole graphite ($n_e = 4$) and F is Faraday's constant. According to the essential thermodynamic relationship: $-\Delta H = -\Delta G - T\Delta S$, the total energy $(-\Delta H)$ consists of two portions, i.e., $(-\Delta G)$ and $(-T\Delta S)$, which represent electrical energy and thermal energy, respectively. As long as the absolute value of the variability in enthalpy is greater than that of the variability in Gibbs free energy, the thermal energy will not be converted into electricity, but will be released as heat [14, 15]. Through this pattern, the power output and efficiency of DCFCs can be expressed respectively as follows:

$$P_{cell} = JA\left(E - V_{act,\mathrm{an}} - V_{act,\mathrm{cat}} - V_{ohm} - V_{con}\right), \qquad (2)$$

and

$$\eta_{cell} = \frac{P_{cell}}{-\Delta\dot{H}} = -\frac{n_e F}{\Delta h}\left(E - V_{act,\mathrm{an}} - V_{act,\mathrm{cat}} - V_{ohm} - V_{con}\right), \qquad (3)$$

where $E = -\frac{\Delta g^0(T)}{n_\mathrm{e} F} + \frac{RT}{n_e F}\ln\left[\frac{p_{\mathrm{O}_2,\mathrm{cat}}\left(p_{\mathrm{CO}_2,\mathrm{cat}}\right)^2}{p_{\mathrm{CO}_2,\mathrm{an}}}\right]$ is the open circuit voltage which can be obtained by the Nernst equation. R is the universal gas constant; J is the working current density; the subscripts "cat" and "an" indicate "cathode" and "anode", respectively; p is the partial pressure of specimen; $\Delta g^0(T)$ is the Gibbs free energy variability at the normative pressure (1 atm); V_{act} , V_{ohm}

and V_{con} are irreversible losses, which represent the activation overpotential, the ohmic overpotential and concentration overpotential respectively.

3. THE EXPRESSIVENESS OF A HEAT-DRIVEN REFRIGERATOR

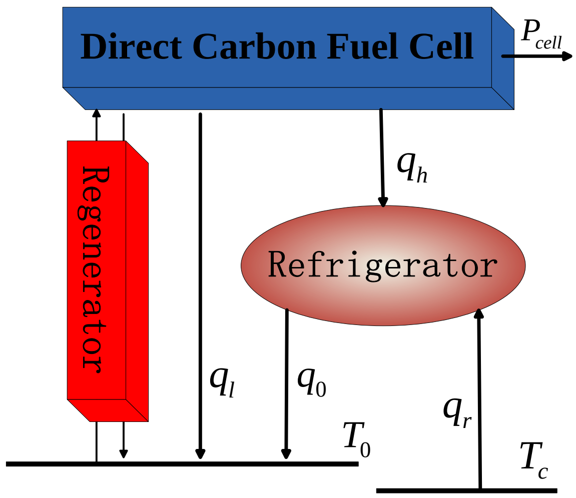

Figure 1. The schematic diagram of a new hybrid system

When the DCFCs are working, there is a lot of high quality squandering heat generated from the DCFC stack. In order to make better use of this part of squandering heat, an absorption refrigerator can be introduced to guarantee the normal operation of the DCFC. Heat rather than work drives directly the refrigerator. Such a heat-driven refrigerator is often referred to as the three-heat-source refrigerator [18]. As shown in Fig. 1, DCFC is the high-temperature reservoir of the absorption refrigerator whose role is to utilize the squandering heat generated from the DCFC stack. Meanwhile, using the high temperature outlet gas of DCFC, the regenerator can be introduced into the mixing department as a heat exchanger to preheat the inlet reactant from the ambient temperature to the required temperature of DCFC. Then, the inlet reactant will flow back to the fuel cell.

Similar method has already been reported several times. A lot of theoretical and experimental researches have been done to prove that squandering heat generate by fuel cell can be used to drive the heat engine. For example Silveira built a fuel cell cogeneration system, which achieved both the high efficiency and the low emission of pollutants [19]. Chen [13-15] also analyzed the performance of fuel cell-heat engine hybrid system. These previous studies play an important foundation to the further research of DCFC-based cogeneration systems.

For the sake of simplicity, the above process is considered to be an ideal regenerative process. As illustrated in Fig. 1, T_C is the cold temperature, T_0 is the ambient temperature, P_{cell} is the power output of the DCFC, q_l is the heat leak rate from the DCFC to the surrounding and q_h , q_0, q_r are the rate of heat flow respectively. Through such a coupled system, the squandering heat generated by DCFC can be immediately applied by the refrigerator. The coupled system can achieve the dual efficiency of DCFC and refrigeration.

As shown in figure 2, a portion of squandering heat will be essential immediately released into the surrounding in the form of heat leakage. The heat flow rate of this portion can be expressed as follows[20-22]:

$$q_l = K_l A_l (T - T_0) \quad (4)$$

where K_l denotes the convective heat-leak coefficient, and A_l is the valid heat-transfer area. Through the first law of thermodynamics, the heat flow rate from DCFC to refrigerator can be obtained:

$$q_h = -\Delta\dot{H} - P_{cell} - \dot{Q}_{loss}$$
$$= -\frac{A\Delta h}{n_e F}\left[\left(1-\eta_{cell}\right) j - C_1(T-T_0)\right] \quad (5)$$

where $C_1 = -\frac{\alpha A_l n_e F}{A\Delta h}$. For the given q_h, one can obtain the optimal expression expressiveness coefficient and rate of refrigeration from the Newton's law, which is as follows:

$$\varepsilon = \left\{\frac{1}{4}d^2 - \frac{T_c}{T}\left[\frac{(a-1)^2}{a^2} - \frac{1}{C_2}\frac{T-T_0}{\left(1-\eta_{cell}\right) j - C_1(T-T_0)}\right]\right\}^{1/2} - \frac{1}{2}d \quad (6)$$

and

$$q_r = q_h\varepsilon = -\frac{A\Delta h}{n_e F}\left[\left(1-\eta_{cell}\right) j - C_1(T-T_0)\right]\varepsilon \quad (7)$$

where $a = \left(\frac{1}{\sqrt{U_c}} + \frac{1}{\sqrt{U_0}}\right)\left(\frac{1}{\sqrt{U_c}} - \frac{1}{\sqrt{U_h}}\right)^{-1}$, $C_2 = \frac{-AC\Delta h}{n_e F}$, $C = \frac{1}{A}\left(\frac{1}{\sqrt{U_c}} + \frac{1}{\sqrt{U_0}}\right)^2$ and $d = 1 + \frac{(a-1)^2 T_c - T_0}{Ta^2} - \frac{1}{C_2}\frac{T_c - T_0}{\left[\left(1-\eta_{cell}\right) j - C_1(T-T_0)\right]}$

4. THE POWER OUTPUT AND EFFICIENCY OF THE COUPLED SYSTEM

Through Eqs. (2), (3) (6) and (7), we can obtain the equivalent power output and efficiency expressions of the coupled system as

$$P = P_{cell} + q_r\left(\frac{T_0}{T_c} - 1\right)$$
$$= -\frac{A\Delta h}{n_e F}\left\{ j\eta_{cell} + \varepsilon\left(\frac{T_0}{T_c} - 1\right)\left[\left(1-\eta_{cell}\right) j - C_1(T-T_0)\right]\right\} \quad (8)$$

and

$$\eta = \eta_{cell} + \varepsilon\left(\frac{T_0}{T_c} - 1\right)\left[1 - \eta_{cell} - \frac{C_1}{j}(T-T_0)\right] \quad (9)$$

Because $q_r\left(\frac{T_0}{T_c} - 1\right)$ in equation (8) must be a positive value and $\varepsilon\left(\frac{T_0}{T_c} - 1\right)\left[1 - \eta_{cell} - \frac{C_1}{j}(T - T_0)\right]$ in equation (9) is the same, it can be seen that the power output and efficiency of the coupled system have been increased comparing with that of a single DCFC.

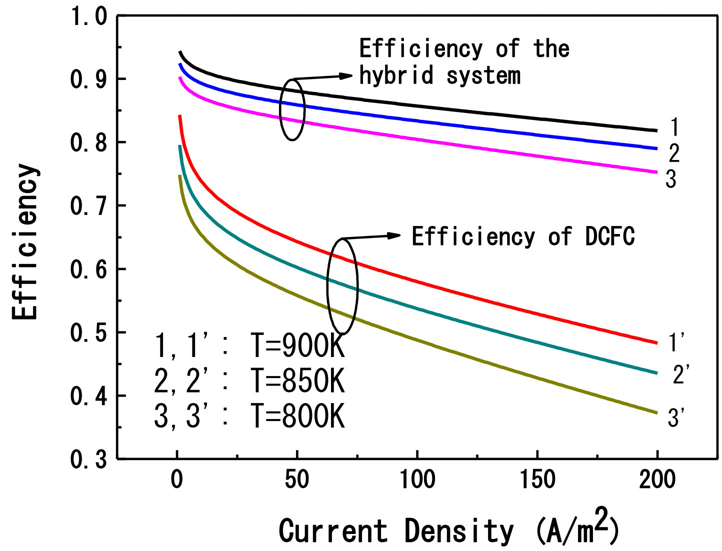

Figure 2. The curves of energy conversion efficiency of the coupled system and DCFC varying with current density of the DCFC.

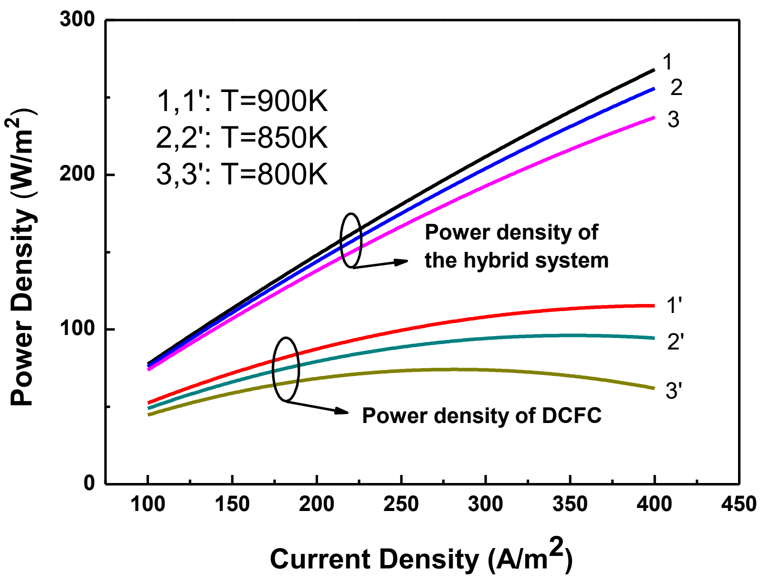

Figure 3. The curves of power density of the coupled system and DCFC varying with current density of the DCFC.

In order to get quantitative assessment of the performance of coupled system, numerical calculations are carried out. Through Eqs. (8) and (9), one can generate the curves of the equivalent power output and efficiency of the coupled system varying with the current density, as shown in Figures 2 and 3, where $P^* = P / A$ is the power density. Fig. 2 shows that efficiency of the coupled system comparing with the sole fuel cell decreases slowly with the increasing of the current density. The maximum energy conversion efficiency of the coupled system is about 95% when the temperature is

900K. However, the efficiency of a single fuel cell is only about 85% under the same condition. The efficiency of the coupled system is larger than the sole DCFC, because the squandering heat in DCFC is utilized by refrigerator. Fig. 3 shows the power density has been significantly improved through the combination of a direct carbon fuel cell and a refrigerator at different temperature. In addition, the performance of the coupled system increases as the operating temperature rises, as shown in the figures. The higher the operating temperature in a reasonable range, the better the performance of the coupled system. Meanwhile, the operating temperature T of DCFC is also an momentous parameter for the coupled system, which immediately affects the value of the several over potential in the fuel cell and the efficiency of the refrigerator. So, the choice of temperature is critical.

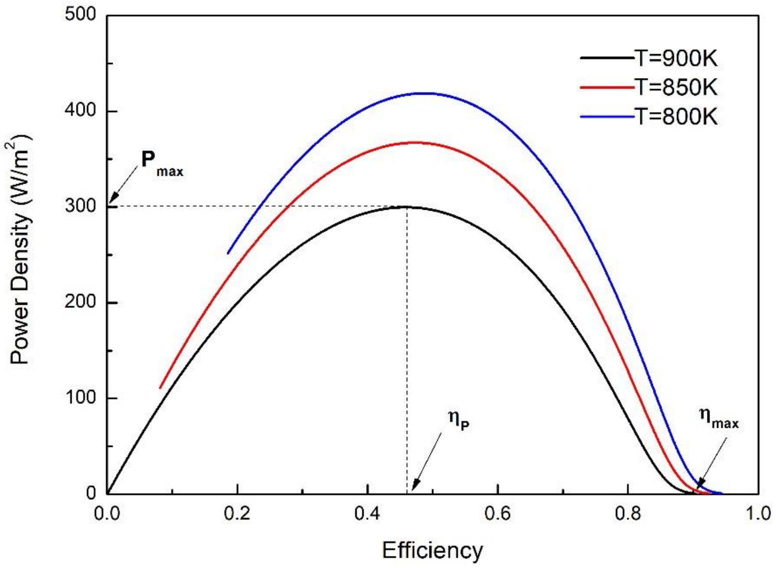

Figure 4. The efficiency versus power density curve of the coupled system.

Figure 4 shows the efficiency versus the power density at different operating temperature, where η_p is the effiency at the maximum power output P_{max}, η_{max} is the maximun efficiency. According to Fig. 5, one can determine the optimal working interval, which has a negative slop in the part of η~P curve. When the coupled system works in this region, the efficiency will increase as the power density decrease, and vice versa. Thus, the optimal efficiency region is given as $\eta_p < \eta < \eta_{max}$. The above analyzes show that η_p is an important coefficient to the coupled system, because it can determine the lower bound of the efficiency.

5. CONCLUSIONS

This paper focuses on the establishment of a coupled system that can utilize the high temperature squandering heat generated by DCFCs. It is found that the power density and efficiency can be greatly improved by connecting the refrigerators to generate electricity further. In addition, with the increase of working temperature, the expressiveness of DCFC will be slightly improved. The results obtained above are more inclined to research the steady state, which means that under certain conditions, the state can be achieved. It can provide theoretical direction for the practical application of DCFCs.

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