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Short Communication

Performance Analysis of Direct Carbon Fuel Cell-Braysson Heat Engine Coupling System

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In this paper, a new coupling system with irreversible Braysson based direct carbon fuel cell is constructed. The new irreversible coupling system can utilize the high quality waste heat generated in the working process of direct carbon fuel cell to drive the irreversible Braysson heat engine, so as to improve the overall working performance. The analytical expressions of direct carbon fuel cell, irreversible Braysson heat engine and coupling system are given respectively, and the performance of the newly constructed coupling system is obviously better than that of the single direct carbon fuel cell.

Keywords: irreversible Braysson heat engine; Direct carbon fuel cell coupling system; Performance analysis

1. INTRODUCTION

After the industrial revolution in the 18th century, coal, as the main fossil energy, was praised as the food of industry, the black gold. Even today, coal is still one of the important energy sources indispensable to human production and life. In 2018, China's normal coal production capacity was 3.61 billion tons, accounting for eight of the world's top ten coal enterprises [1]. At present, more than 60% of China's electricity is generated by coal. However, the direct combustion of coal will produce a large number of greenhouse gases and pollutants, such as SO_x and NO_x, which will adversely affect people's life and plant growth [2]. At the same time, traditional power generation methods all have a process of "chemical energy → thermal energy → kinetic energy" energy conversion and transfer, and the conversion efficiency is often not high, usually only 33%~35%, and nearly two-thirds of the energy is lost in the process of energy conversion [3].

Direct carbon fuel cell (DCFC) is an energy conversion device that converts the chemical energy in carbon directly into electrical energy by means of electrochemical oxidation process, and the whole conversion process does not require combustion or gasification [4-7]. Its fuels are extremely extensive, including petroleum coke, coal, gas charcoal and biochar [8]. Direct carbon fuel cells not only have relatively high energy conversion efficiency, but their efficiency is two or three times that of traditional thermal power generation. Moreover, due to no combustion, the whole process hardly emits SO_x , NO_x and other pollutants [9].

Although direct carbon fuel cells have been widely studied, how to use direct carbon fuel cell devices to generate electricity is still to be determined. Generally speaking, the operating temperature of direct carbon fuel cell is relatively high. For example, MC-DCFC with molten carbonate as electrolyte, its operating temperature range is about 700~800 ^oC [10], during which a large amount of high-quality waste heat is generated. Although the power generation efficiency of direct carbon fuel cell system is much higher than that of traditional power generation, it still has the potential to improve the power generation efficiency and increase the energy utilization rate of the system due to the existence of high-quality waste heat. Therefore, it is an important way to improve the energy conversion efficiency of direct carbon fuel cell to build the coupling system between direct carbon fuel cell and thermal engine, which has great practical application value.

How to better improve the performance of direct carbon fuel cells has always been the most concerned problem for scientific researchers. Some researchers [11,12] found that the overall performance of direct carbon fuel cells could be improved by changing the anode material. Other work [13,14] focuses on the research and exploration of different electrolytes, so as to improve the overall performance by changing the interaction between carbon fuel and electrolytes. At the same time, there is also a lot of work [15-18] to study waste heat utilization of direct carbon fuel cells, for example, through coupling thermoelectric generator [15], vacuum thermionic generator [16], thermal photovoltaic cell [17], Breton engine [18] and other energy devices, to improve the performance of the overall coupling system. In this paper, a new direct carbon fuel cell-to-thermo coupling system is constructed by using irreversible Braysson heat engine as the carrier of waste heat utilization of direct carbon fuel cell. By means of numerical simulation, some preliminary research on the Braysson based direct carbon fuel cell coupling system was carried out, which not only considered various irreversible losses inside the fuel cell, but also considered the heat leakage between the fuel cell and the engine, and revealed the influence of various parameters on the overall performance of the coupling system.

2. DIRECT CARBON FUEL CELL

The configuration and theoretical principle of direct carbon fuel cell are similar to other high temperature fuel cells, such as molten carbonate fuel cell and solid oxide fuel cell. The direct carbon fuel cell is mainly composed of three parts, they are anode, cathode and electrolyte. However, unlike other high-temperature fuel cells, direct carbon fuel cells can use solid carbon as fuel without gasification. Under the high temperature (973K~1073K) working environment, a series of chemical reactions occurred in the cathode region and anode region of direct carbon fuel cell. The total chemical reaction formula is $C + O_2 \rightarrow CO_2$. The analytical expressions of the output power and efficiency of direct carbon fuel cell can be obtained by using the model of Zhang et al. [19] :

$$P_{\rm cell} = JA\left(E - V_{\rm act,an} - V_{\rm act,cat} - V_{\rm ohm} - V_{\rm con}\right), \quad (1)$$

和

$$\eta_{\rm cell} = \frac{P}{-\Delta \dot{H}} = -\frac{n_e F}{\Delta h}\left(E - V_{\rm act,an} - V_{\rm act,cat} - V_{\rm ohm} - V_{\rm con}\right), \quad (2)$$

其中：

$$E = -\frac{\Delta g^0(T)}{n_{\rm e}F} + \frac{RT}{n_{\rm e}F}\ln\left[\frac{p_{\rm O_2,cat}\left(p_{\rm CO_2,cat}\right)^2}{p_{\rm CO_2,an}}\right], \quad (4)$$

$$V_{\rm act,an} = \frac{RT}{2F}\ln\left[\frac{J}{2K_{\rm B}\exp(-E_{\rm B}/T)} + \sqrt{\left(\frac{J}{2K_{\rm B}\exp(-E_{\rm B}/T)}\right)^2 + 1}\right], \quad (5)$$

$$V_{\rm act,cat} = \frac{RT}{2F}\ln\left[\frac{J}{2J^0_{\rm 0,cat}(p_{\rm CO_2,cat})^{r_1}(p_{\rm O_2,cat})^{r_2}} + \sqrt{\left(\frac{J}{2J^0_{\rm 0,cat}(p_{\rm CO_2,cat})^{r_1}(p_{\rm O_2,cat})^{r_2}}\right)^2 + 1}\right], \quad (6)$$

$$V_{\rm ohm} = \sum_{i=1}^{N_s} J\frac{D_c}{\sigma^0_{\rm s}\varepsilon^{1.5}\exp(-E_{\rm a}/RT)}\left[1 - \frac{N_{\rm e}}{LW}\sqrt{\frac{(N_{\rm s}-i)F_{\rm g} - F_{\rm r}}{\pi c M}}\right]$$
$$+ \sum_{i=1}^{N_{\rm s}} JN_{\rm e}\frac{\sqrt{3}D_{\rm c}^2}{4LW\sigma_{\rm c,0}}\sqrt{\frac{(N_{\rm s}-i)F_{\rm g} - F_{\rm r}}{\pi c M}}$$
$$+ J\left[\frac{Q}{p^{0.67}_{\rm O_2,cat}}\exp(B/T) + C_{\rm R} + D\exp(f/T)\right], \quad (7)$$

$$V_{\rm con} = \frac{RT}{n_{\rm e}F}\ln\left(\frac{J_{\rm lim}}{J_{\rm lim} - J}\right) \quad (8)$$

where J is the working current density; The subscripts "an" and "cat" represent anode and cathode respectively. p_k is the partial pressure of k at the anode or cathode. $\Delta g^0(T)$ under normal atmospheric pressure of Gibbs free energy change; N_s is the number of layers of carbon particles. F_g represents the gravity of carbon particles; F_r represents the repulsive force between carbon particles. ε is the void ratio of the filling layer; $\sigma_{c,0}$ is the conductivity of carbon particles. M is the pressure within the elastic limit; c is the irregularity coefficient of carbon surface.

3. IRREVERSIBLE BRAYSSON HEAT ENGINE

Through the basic thermodynamic relationships $-\Delta H = -\Delta G - T\Delta S$, with the direct carbon fuel cell power generation, there will always be part of the energy $(-T\Delta S)$ cannot be converted into electrical energy, and must be released in the form of heat to the outside world. This part of energy can be reused as a high temperature reservoir for an irreversible Braysson engine to drive a Braysson engine. The total heat transferred to Braysson heat engine can be expressed as:

$$q_h = -\Delta\dot{H} - P_{cell} - \dot{Q}_{loss} - \dot{Q}_{re}$$
$$= -\frac{\Delta h}{n_e F}jA - U_{cell}jA - \alpha_l A_l(T - T_0) - k_{re}(1-\varepsilon)(T - T_0). \quad (9)$$

where $-\dot{\Delta H}$ is the total energy released per unit time, P_{cell} is the power output of direct carbon fuel cell, $\dot{Q}_{loss}$ is the heat leakage of direct carbon fuel cell in the unit time, A_l is the heat transfer area, T_0 is ambient temperature, T is the operating temperature of direct carbon fuel cell.

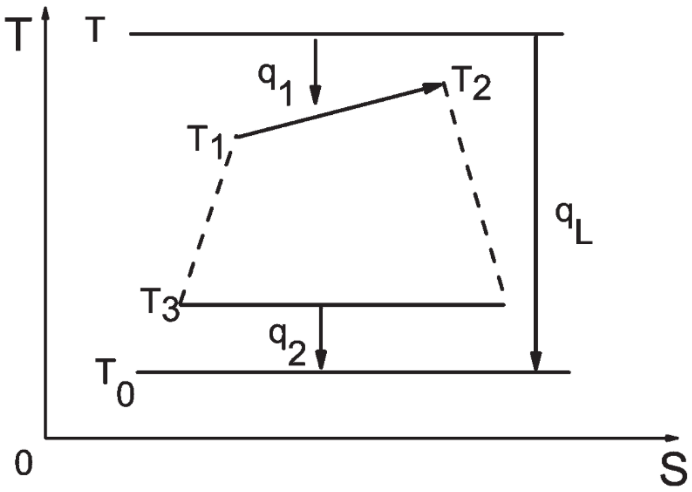

Figure 1. schematic of the Braysson engine

As shown in figure 1, the engine is composed of an isothermal process, an isobaric process, and two adiabatic processes. Given the heat input, the optimal working efficiency and output power of the irreversible Braysson heat engine [20] can be expressed as:

$$\eta_h = 1 - \frac{RT_0 \ln x}{T_1(x-1)(1-d_2)} \tag{10}$$

and

$$P_h = q_h\eta_h = \alpha A_e \left[C_1(1-\eta_{cell})j - \left(\frac{T}{T_0} - 1\right)(C_2 + C_3)\right] \times \left[1 - R_h \frac{(y-1)(1-e^b)\ln(x)T_a}{(x-1)(1-e^b)\ln(y)T_1}\right] \tag{11}$$

where $y = \frac{T_h - T_1}{T_h - xT_1}$, $x = T_2/T_1$, $b = \left[\frac{1}{B_h} - \frac{\ln u}{(x-1)T_1}\right]\frac{\beta(x-1)\ln(y)T_1}{\alpha R \ln x}$.

4. COUPLING SYSTEM

A new irreversible Braysson based direct carbon fuel cell coupling system is constructed. The new irreversible coupling system can utilizes the high quality waste heat generated in the working process of direct carbon fuel cell to drive the irreversible Braysson heat engine. Through equations (1) ~ (11), the expressions of efficiency and power output of the coupling system can be obtained as follows:

$$\eta_{hybrid} = \eta_{cell} + \left[1 - \eta_{cell} + \frac{1}{JC_1}(\frac{T}{T_0} - 1)(C_2 + C_3)\right] \times \left[1 - R_h \frac{(y-1)(1-e^b)\ln(x)T_a}{(x-1)(1-e^b)\ln(y)T_1}\right], \tag{12}$$

and

$$P_{hybrid} = -jA\frac{\Delta h}{n_e F} \times \left\{\eta_{cell} + \left[1 - \eta_{cell} + \frac{1}{JC_1}(\frac{T}{T_0} - 1)(C_2 + C_3)\right] \times \left[1 - R_h \frac{(y-1)(1-e^b)\ln(x)T_a}{(x-1)(1-e^b)\ln(y)T_1}\right]\right\}. \tag{13}$$

From equation (12), the value of $\left[1-\eta_{cell}+\frac{1}{JC_1}\left(\frac{T}{T_0}-1\right)(C_2+C_3)\right]\times\left[1-R_h\frac{(y-1)(1-e^b)\,ln(x)T_a}{(x-1)(1-e^b)\,ln(y)T_1}\right]$ is always positive, so the efficiency of the coupling system is always better than the single direct carbon fuel cell. And the equation (13) is also in the same way, the total power output of the coupled system is better than the single direct carbon fuel cell.

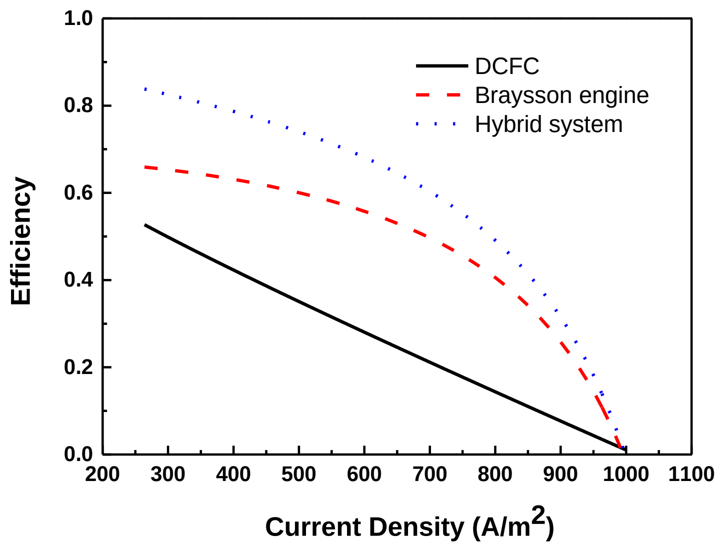

Figure 2. the curves of current density versus efficiency

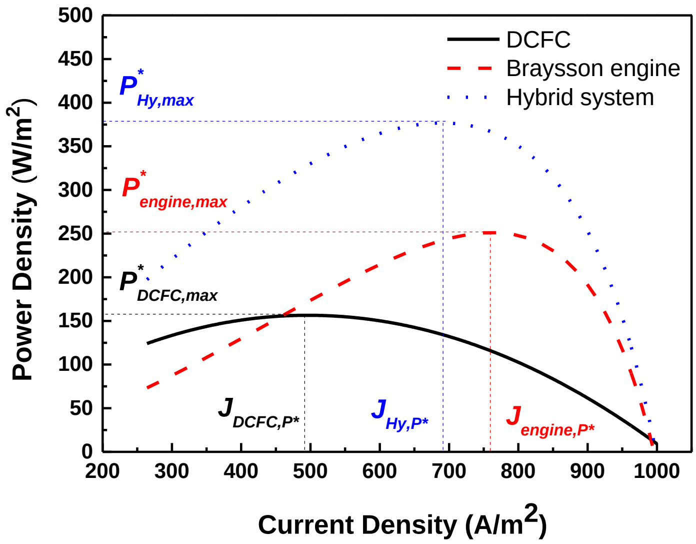

Figure 3. the curves of current density versus power density

Figure 2 and figure 3 show the performance curves of direct carbon fuel cell, Braysson engine and coupling system as the current density changes. Where, P/A is defined as power density, which can be used to characterize the physical quantity of power. As can be seen from the figure, the overall performance of the system, both power and efficiency, has been significantly improved due to the coupling of the irreversible Braysson engine. As can be seen from figure 2, in the region of effective working current density ranging from 250 to 1000A/m^2, the efficiency decreases monotonically with the increase of working current density. The lower the current density, the higher the efficiency. In figure 3, the change of power is not a monotonic curve. Direct carbon fuel cell, Braysson engine and coupled system have their own extreme values, and they are not equal with each other. The current corresponding to the maximum power of the coupled system is not the operating current of a single fuel cell at maximum power, nor is it the operating current of a single heat engine at maximum power, and the value is in between. At the same time, it can be seen from figure 2 that when the working current is smaller, the efficiency of the system is higher. Therefore, in engineering, the power preference or efficiency preference of engineers determines the choice of working current. But anyway, the current density must be in the range of $(0, J_{Hy,P^*}]$. It can also be seen from figure 2 and figure 3 that the performance of the whole coupling system has been greatly improved compared with that of a single direct carbon fuel cell by connecting the thermal engine, a secondary energy device. Similar conclusions have been found many times in other papers. A coupling system is constructed by coupling different heat engines, such as Stirling engine[21], Carnot engine[22], etc., to improve the performance of the overall system. However, the discussion on direct carbon fuel cell-Braysson engine is still the first time.

5. CONCLUSION

In this paper, a new direct carbon fuel cell-braysson heat engine coupling system is constructed. As a secondary energy device of direct carbon fuel cell, braysson heat engine can utilize the waste heat generated in the working process of direct carbon fuel cell to drive the thermal engine, thus improving the overall working performance. Analytical expressions of direct carbon fuel cell, Braysson heat engine and coupling system are obtained through analytical derivation. Moreover, it is mathematically proved that the performance of the coupled system is greatly improved due to coupling the Braysson heat engine.

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