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Exergy Analysis of a Novel SOFC Hybrid System with Zero-CO₂ Emission

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1. Introduction

Now, climate change due to the emission of greenhouse gases, especially the emission of CO₂, is becoming more and more serious. Though many countries have taken all kinds of measures to control and reduce the emission of CO₂, in the short term, CO₂ emission still maintains a rapid growth trend. Power industry is the biggest CO₂ emission sector. So, there exists the greatest CO₂ emission reduction potential in the power industry. Now, many kinds of fossil fuel power generation systems with CO₂ recovery are usually based on the chemical absorption method or the oxygen combustion method. The former demands a chemical absorption and separation unit to recover CO₂ from the flue gas of power systems. The latter demands a special oxygen combustion technology, equipment and a larger ASU (air separation unit). And these technologies all consume great energy and result in the huger equipment investment and higher operating cost. Now, people are eager to develop the high-efficiency power generation technology with the less energy consumption for CO₂ capture. Fuel cell can satisfy the above requirements, with the higher energy conversion efficiency and less energy consumption of CO₂ capture, so it has attracted considerable interest in recent years.

Solid Oxide Fuel Cell (SOFC) is an attractive power-generation technology that can convert the chemical energy of fuel directly into electricity while causing little pollution (Karthi & Grimes, 1994). Because the anode fuel gas is naturally separated from the cathode air by the solid electrolyte, the CO₂ gas with the higher concentration can be obtained in the anode exhaust gas. In addition, SOFC can employ all kinds of fuels, including various hydrocarbon fuels. Compared with the traditional power generation systems, the SOFC hybrid system power plant has the higher system efficiency (net AC/LHV). Even after CO₂ is captured, the efficiency of SOFC hybrid system still can be greater than or equal to that of the traditional power systems without CO₂ capture. In order to further improve the CO₂ concentration of anode exhaust gas, SOFC can employ the O₂/CO₂ combustion mode in the afterburner. Because the required mass flow of pure O₂ is less, the energy consumption is lower. After capturing the CO₂, the SOFC hybrid system does not result in a bigger efficiency reduce. So the SOFC hybrid power system with zero CO₂ emission become a new way which can

simultaneously solve the problem of efficient energy utilization and lower pollution emission.

In the last decades, many researchers were involved in study of SOFC stack and the hybrid power system with CO₂ capture. Y.Inui proposed and investigated two types of carbon dioxide recovering SOFC/GT combined power generation systems in which a gas turbine with carbon dioxide recycle or water vapor injection is adopted at the bottoming cycle system (Y.Inui et al, 2005). The overall efficiency of the system with carbon dioxide recycle reaches 63.87% (HHV) or 70.88% (LHV), and that of the system with water vapor injection reaches 65% (HHV) or 72.13% (LHV). A. Franzoni considered two different technologies for the same base system to obtain a low CO₂ emission plant (Franzoni et al, 2008). The first technology employed a fuel decarbonization and CO₂ separation process placed before the system feed, while the second integrated the CO₂ separation and the energy cycle. The result showed that the thermodynamic and economic impact of the adoption of zero emission cycle layouts based on hybrid systems was relevant. Philippe Mathieu presented the integration of a solid oxide fuel cell operating at a high temperature (900°C–1000°C, 55–60% efficiency) in a near-zero emission CO₂/O₂ cycle (Philippe Mathieu, 2004). Takeshi Kuramochi compared and evaluated the techno-economic performance of CO₂ capture from industrial SOFC-combined heat and power plant (CHP) (Takeshi et al, 2009). CO₂ is captured by using an oxyfuel afterburner and conventional air separation technology. The results were compared to both SOFC-CHP plants without CO₂ capture and conventional gas engines CHP without CO₂ capture. B.Fredriksson Moller examined the SOFC/GT configuration with and without a tail-end CO₂ separation plant, and based on a genetic algorithm, selected the key parameters of the hybrid system (Fredriksson et al, 2004). The result of the optimization procedure shows that the SOFC/GT system with part capture of the CO₂ exhibits an electrical efficiency above 60%. Some researchers also studied the performance parameters of the different SOFC hybrid power systems from the thermoeconomic or exergy efficiency point (Bozzolo et al, 2003; Asle & Matteo 2001; Takuto et al, 2007). For example, Ali Volkan Akkaya proposed a new criterion-exergetic performance coefficient (EPC), then applied it in the SOFC stack and SOFC/GT CHP system (Ali et al, 2007, 2009). F. Calisa discussed the simulation and exergy analysis of a hybrid SOFC-GT power system. The result showed that the SOFC stack was the most important sources of exergy destruction (Calisea et al, 2006).

In this paper, a zero-CO₂ emission SOFC hybrid power system is proposed. Using exergy analysis method, the exergy loss distributions of every unit of zero-CO₂ emission SOFC hybrid system are revealed. The effects of different operating parameters on exergy loss of every unit, as well as the overall system performance, are also investigated. The results obtained in this paper will provide useful reference for further study on high-efficient zero emission CO₂ power system.

2. System modelling

The models developed in the paper are all based on the following general assumptions:

1. All components work in adiabatic conditions, pressure drops and refrigerant disclosure are all neglected, and the systems operate at steady-state conditions.
2. The cathode gas consists of 79% nitrogen and 21% oxygen, and all gases are assumed as ideal gases.

3. The mass flow of the input fuel, gas and all the reaction products are stable, the changes of the fluid kinetic energy and potential energy are neglected.
4. The unreacted gases are assumed to be fully oxidized in the after-burner of the SOFC stack, and the after-burner is assumed to be insulation, all the heat exchangers are adiabatic.
5. The temperature of the anode and cathode outlet gases are equal to the cell stack operating temperature, the current and voltage of every cell unit are the same.

2.1 The SOFC stack model and result analysis

2.1.1 SOFC model

The natural gas feed tubular SOFC system process is implemented by using Aspen Plus software. The Aspen Plus contains rigorous thermodynamic and physical property database and provides comprehensive built-in process models, thus offering a convenient and time saving means for chemical process studies, including system modeling, integration and optimization. The simulated SOFC flowsheet is shown in Figure 1. It includes all the components and functions contained in the SOFC stack, such as ejector, pre-reformer, fuel cell (anode and cathode) and afterburner.

Firstly, the preheated fuel (stream 1) mixes with the recycling anode exhausted gas (stream 6), and then the mixed fuel gas (stream 2) is sent to the pre-reformer where the steam reform reaction takes place. After that, the stream (4) enters the anode of SOFC in which the electrochemical reaction of fuel and oxygen from the anode occurs. The reaction product and unreacted flue mixture (stream 5) is separated into two parts. One part (stream 6) is recycled. Another part enters the afterburner and mixes with the nitrogen-rich air (stream 13) from the anode. After the combustion reaction, the exhausted gas from the afterburner (stream 14) is introduced into the regenerator to preheat the air (stream 9) for the anode.

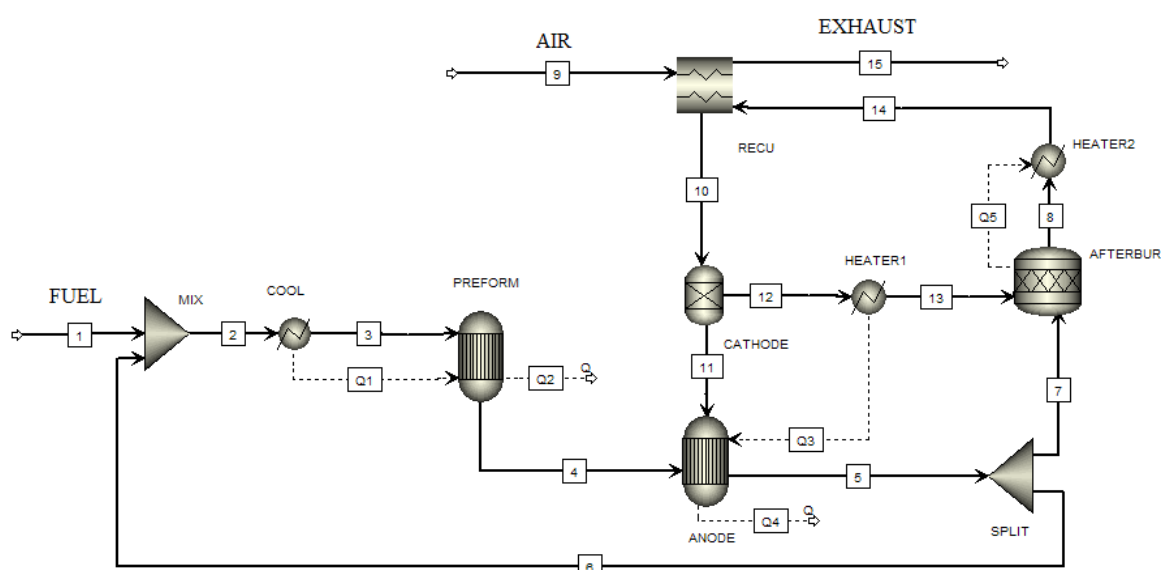


Fig. 1. Aspen Plus SOFC Stack Model Flowsheet

The cell voltage calculation is the core of any fuel cell modeling. The semi-empirical equations from literature (Stefano, 2001) were used to compose the Aspen Plus calculation module to simulate these effects on voltage. Several Design-spec Fortran blocks are used to set the fuel cell system's energy and heat balance. The semi-empirical equations are as follows:

$$\Delta V_p (\text{mV}) = C_1 \log\left(\frac{p}{p_{ref}}\right) \quad (1)$$

$$\Delta V_T (\text{mV}) = K_T (T - T_{ref}) \times i_c \quad (2)$$

$$\Delta V_{an} (\text{mV}) = 172 \log \frac{p_{H_2}/p_{H_2O}}{(p_{H_2}/p_{H_2O})_{ref}} \quad (3)$$

$$\Delta V_{cat} (\text{mV}) = 92 \log \left(\frac{p_{O_2}}{(p_{O_2})_{ref}} \right) \quad (4)$$

By summing the above four correlations, the actual voltage V can be calculated as

$$V_c = V_{ref} + \Delta V_p + \Delta V_T + \Delta V_{cat} + \Delta V_{an} \quad (5)$$

Where i_c is the current density; p_{H_2}/p_{H_2O} is the ratio of H_2 and steam partial pressure; p_{O_2} is the average oxygen partial pressure at the cathode for the actual case; V_c is the actual cell voltage; the subscript ref is the reference case. $P_{ref} = 1 \text{ bar}$; $T_{ref} = 1000^\circ\text{C}$; $(p_{O_2})_{ref} = 0.164$; $(p_{H_2}/p_{H_2O})_{ref} = 0.15$. ΔV_P stands for the change of SOFC voltage when the operating pressure varies. C_1 is the theoretical Nernst constant. ΔV_T stands for the change of SOFC voltage when the operating temperature varies. K_T is equal to 0.008 when the operating temperature is in the range of $900\text{--}1050^\circ\text{C}$. ΔV_{cat} and ΔV_{an} stand for the voltage change when the cathodic flow composition and anode flow composition vary compared with the reference case, respectively.

The fuel cell power output is the product of the cell voltage and current.

$$\text{Power} = \text{current}(A) \times V(V) \quad (6)$$

The equivalent hydrogen flow rate $n_{H_2, \text{equivalent}}$, can be calculated based on the molar flow rate of H_2 consumed in the electrochemical reaction ($n_{H_2, \text{consumed}}$) and the fuel utilization factor (U_f) to be generated:

$$n_{H_2, \text{equivalent}} (\text{mol} / \text{h}) = \frac{n_{H_2, \text{consumed}}}{U_f} \quad (7)$$

The value of the equivalent hydrogen flow rate and the known inlet fuel composition (C_i) can determine the amount of fresh fuel required $n_{\text{fresh, fuel}}$ from the following equation (8):

$$n_{\text{fresh, fuel}} (\text{mol} / \text{h}) = \frac{n_{H_2, \text{equivalent}} (\text{mol} / \text{h})}{C_{H_2} + C_{CO} + 4 \times C_{CH_4} + 7 \times C_{C_2H_6} + \dots} \quad (8)$$

The cell electrical efficiency is calculated according to the following equation (9):

$$\eta = \frac{\text{Power}}{n_{\text{fresh, fuel}} (\text{mol} / \text{h}) \times LHV_{\text{fuel}} (\text{J} / \text{mol})} \quad (9)$$

2.1.2 SOFC simulation result analysis

In the process of modeling the hybrid power system, the accuracy of the fuel cell stack simulation is critical for the overall system. So this paper firstly checked the accuracy of SOFC stack model. With the same input parameters of the literatures (W.Zhang et al, 2005), the simulation results were compared with those of the literatures (W.Zhang et al, 2005,Veyo, 1996,1998,1999) . As shown in Table 1, the results show that this paper’s simulation results are very close to the literature results. So the model of SOFC stack is feasible and reliable, it can be applied to simulate the overall SOFC hybrid system.

Parameters (unit)	Literature Data (W,Zhang et al 2005)	Literature Data (Veyo, 1996,1998, 1999)	Simulation data of this paper
Voltage (V)	0.70	-	0.70
Current Density (mA/cm ²)	178	180	179.1
Air utilization factor	19%	-	18.2%
Pre-reformer Outlet Temperature (°C)	536	550	537.2
Stack Exhaust Composition (EXHAUST)	77.3%N ₂ 15.9%O ₂ 4.5%H ₂ O 2.3%CO ₂	77%N ₂ 16%O ₂ 5%H ₂ O 2%CO ₂	77.5%N ₂ 16.4%O ₂ 4%H ₂ O 2.1%CO ₂
Anode Outlet Composition (stream5)	50.9% H ₂ O 24.9%CO ₂ 11.6%H ₂ 7.4%CO 5.1%N ₂	48% H ₂ O 28%CO ₂ 14%H ₂ 5%CO 5%N ₂	50.9% H ₂ O 24.9% CO ₂ 11.6% H ₂ 7.4%CO 5.1%N ₂
Stack Exhaust Temperature (°C)	834	847	832
Stack Efficiency (AC)	52%	50%	51.99%

Table 1. The Simulation Results of SOFC Stack (120kW DC output)

2.2 Description of the basic SOFC hybrid system

The basic SOFC hybrid system uses a tubular SOFC stack with higher operating temperature. Figure 2 shows the flowsheet of the system. The fuel is compressed and preheated, then is put into pre-reformer to generate the required H₂, CO and CO₂. Air is supplied by a blower and preheated prior to enter the SOFC stack. Then air participates an electrochemical reaction with fuel in the fuel cell stack. Because the pre-reformer needs a larger amount of water vapor, a hot recycle stream from the anode outlet is directed to the pre-reformer. The outlet stream of SOFC anode is mainly composed of H₂O, CO₂ and unconverted fuel (H₂ and CO). Part of this stream is injected into after-burner, then the hot outlet gas with high pressure expands in gas turbine, the rest is recycled and mixed with the compressed and preheated fuel. The recirculation fraction is calculated to obtain a given steam/carbon (S/C) ratio. In this way, the system can prevent from carbon deposition phenomenon, enhance the pre-reformer temperature and get more H₂. Finally, the product gas of SOFC is sent into the after-burner, where the unreacted fuel is burnt with part of the excess air from the cathode. After expansion of the hot gas in gas turbine, it is sent into heat exchangers to heat the inputted fuel and gas. In order to control the outlet gas temperature and prevent the temperature from exceeding the tolerable inlet temperature of the turbine, water vapor is injected into the afterburner.

After the hot outlet gas with high pressure expands in gas turbine, it is fed to recuperator to heat the inputted fuel and air. Finally it is fed to the heat exchanger 4 for producing the saturated water vapor required for the after-burner.

Although SOFC hybrid power system has realized energy conversion with higher efficiency, the hybrid system still emit some greenhouse gas, which contains a large number of N_2 that will greatly impact the energy consumption of capturing CO_2 . The paper proposed a zero CO_2 emission SOFC hybrid power system with water vapor injection and made the detailed exergy analysis on it.

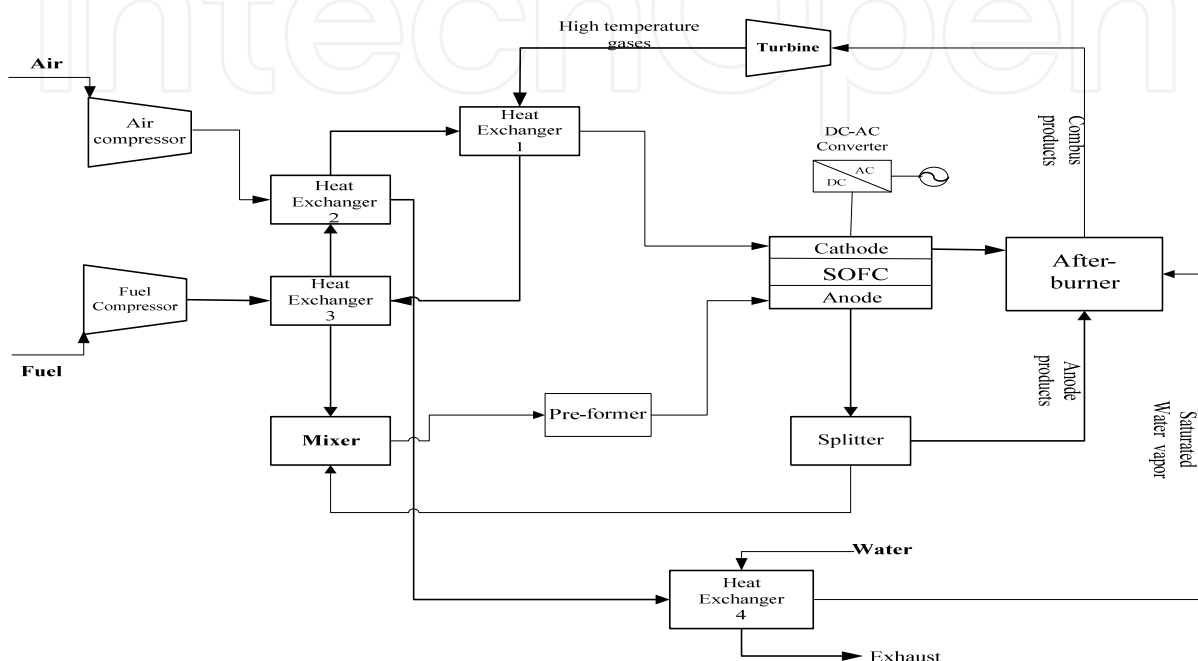


Fig. 2. Flowsheet of the basic SOFC hybrid system

2.3 Description of the new SOFC hybrid system with CO_2 capture

The new system and the basic system's primary processes are the same, but the new system employs O_2/CO_2 combustion mode. Pure oxygen from air separation unit (ASU) is fed into the combustion chamber to burn with the anode exhaust gas. The product gas only contains water vapor and CO_2 . As shown in Figure 3, the compressed and preheated air is supplied to enter the SOFC stack and participate in an electrochemical reaction with fuel in the SOFC stack. At the same time, fuel is supplied by a blower and preheated prior to entering the SOFC stack anode. Part of the anode product gas is recycled to the mixer, and then mixed with the input compressed and preheated air; the remaining stream is burnt in the after-burner using oxygen as the oxidizer. After the combustion products expand in gas turbine, they are fed to heat exchangers to heat the inputted fuel and air. Finally the product gases are injected into the heat exchanger 4 and preheat the feed water for the afterburner. Theoretically the produced steam is enough to reduce the combustion gas temperature to the acceptable inlet temperature of turbine. The obtained combustion gas, which is composed of only CO_2 and water vapor, is introduced to gas turbine. After expansion, the cathode products are also injected into the heat exchanger 4 (also called the fourth heat exchange). Generally, capturing CO_2 is a difficult and complicated process, but the system uses O_2/CO_2 combustion mode, as a result, the combustion product gases only contain water vapor and CO_2 . CO_2 can be separated by condensation, which

does not consume extra energy. Finally it is fed to the multi-stage compressor and makes CO₂ dried from water and liquefied for making the transportation easier.

In order to realize zero CO₂ emission and lower the energy consumption of CO₂ capture, the new system mainly adopts the following measures:

1. In order to prevent the dilution of N₂, only the anode exhaust gas is burned with pure oxygen in the after-burner.
2. In order to enhance the system power, cathode outlet gas of SOFC stack is channeled into turbine to expand. And the product gas is channeled into the heat exchanger 4 to produce enough water vapor for the afterburner.
3. To avoid the great energy consumption, the new system uses multi-stage compression mode. After removing H₂O, the CO₂ concentration of depleted gas is more than 99%.

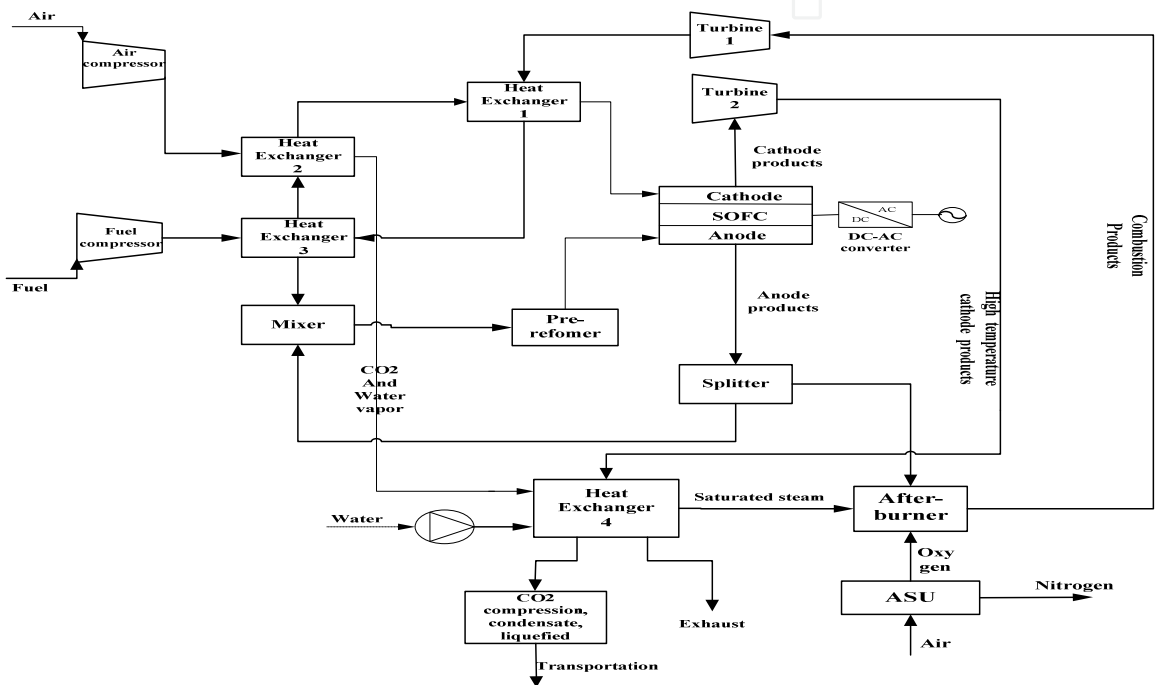


Fig. 3. Flowsheet of the zero CO₂ emission SOFC hybrid system

2.4 Simulation analysis of the basic and the new system

(1) System simulation parameters

The inputted fuel compositions of the basic and the new systems are the same (CH₄ 93.6%, C₂H₆ 4.9%, C₃H₈ 0.4%, C₄H₁₀ 0.2%, CO 0.9%). The fuel utilization factor is 85%, and the air utilization rate is 25%. The SOFC operating temperature/pressure is 1123.15K/3atm. The steam turbine isentropic efficiency is 85% and the gas turbine isentropic efficiency is 80%. The DC to AC inverter efficiency is 92%. The efficiencies of CO₂ compressor and air compressor in ASU are 75%.

(2) The performance analysis of the two systems

Table 2 shows the simulation results of the basic and new systems. For the new system, the cathode gas of the new system has a certain pressure; the new system can recover some expansion work of cathode exhaust gas. Though the new system applies the air separation unit and CO₂ capture equipment, which will consume some energy, compared with the cathode gas expansion work, it can be neglected.

Parameters (unit)	Base case	New system
SOFC Voltage (V)	0.64	0.64
SOFC Current Density (mA/cm ²)	180.54	180.54
SOFC Stack Efficiency (%)	47.98	47.98
Electrical Efficiency (%) (AC)	59.03	56.26

Table 2. The simulation results of the two systems

3. The exergy analysis of the new hybrid system with CO₂ capture

Exergy analysis method is based on the second thermodynamics Law, considering both the energy quantity and energy quality in every energy conversion process. On the base of the energy balance and mass balance, the overall system is divided into many units and the exergy value of every stream is calculated. Through exergy balance analysis, the distributions of exergy loss of every unit can be acquired. At the same time, the system’s largest exergy loss unit can be found. So, the location and direction of reducing exergy loss to improve the efficiency of the system can be identified (Jiaxuan & Shufang 1993).

The total exergy loss ($E_{X_{D,tot}}$) of the hybrid power system is given by the following equation:

$$E_{X_{D,tot}} = E_{X_{D,SOFC}} + E_{X_{D,GT}} + E_{X_{D,ASU}} + \tag{10}$$

Where $E_{X_{D,SOFC}}$ is SOFC stack’s exergy loss; $E_{X_{D,GT}}$ is the turbine’s exergy loss; $E_{X_{D,ASU}}$ is the ASU’s exergy loss;

In order to analyze the system exergy loss in detail, the exergy loss rate (σ_i) is designed as the ratio of every component exergy loss ($E_{X_{D,i}}$) to the total system exergy loss.

$$\sigma_i = \frac{E_{X_{D,i}}}{E_{X_{D,tot}}} \times 100\% \tag{11}$$

The exergy efficiency (η_E) of the SOFC hybrid power system is another important exergetic performance criterion, and it can be defined as the ratio of total system effective acquired exergy to fuel input exergy as the following equation:

$$\eta_E = \frac{W + E_Q}{E_F} \times 100\% \tag{12}$$

Where, W is the system power; E_Q is the acquired heat exergy; E_F is the fuel exergy, and it can be calculated as the following equation:

$$E_F = Q_{DW} \times U_{fuel} \tag{13}$$

Where, Q_{DW} is the lower heating value (LHV) of the input fuel; U_{fuel} is the mass flow rate of fuel.

Exergy analysis takes the environmental state as reference state (P_0, T_0). In this paper, the selected temperature/pressure is 1123.15K/1atm as the reference environment state.

3.1 Exergy loss analysis of the system's every unit

Figure 4 shows the every unit exergy loss of the zero CO₂ emission SOFC hybrid power system. The biggest exergy loss unit lies in SOFC stack, which accounts for more than 35% of the total exergy loss. The main reason is that excess air is injected into to the SOFC stack in order to reduce the temperature difference of SOFC stack, and part of the input fuel chemical energy heats the excess air, which will cause a significant irreversible loss. One part of energy generated by electrochemical reaction is directly converted into the electrical energy, while the other part is changed into heat power to ensure that the fuel is reformed into H₂. So it makes the useful work generated by the fuel chemical energy reduce and the exergy loss increase.

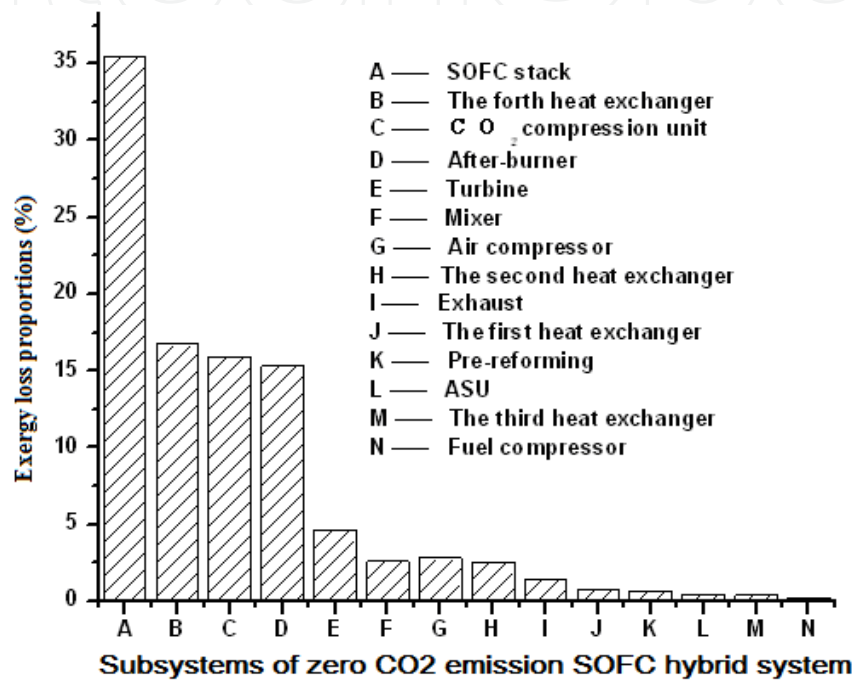


Fig. 4. Exergy loss distributions of Zero CO₂ emission hybrid power system units

According to the Second Law of Thermodynamics, even the heat loss of heat exchanger is neglected, there is still irreversible exergy loss in the inside of heater caused by big temperature difference heat transfer and mucous membrane resistance in the flow process of cold and hot fluid (Calise et al, 2006). As shown in Figure 4, the exergy loss of the fourth heat exchanger is the second biggest. In order to effectively reduce the exergy loss of heat exchangers, the heat transfer process should be designed reasonably in order to reduce the temperature difference.

3.2 Parametric exergy analysis results and discussions

The operating temperature, the operating pressure, the current density and fuel utilization factor of SOFC system are all considered as key variables which greatly influence the overall system performance. In the following discussion, the effects of the above key variables on the exergetic performance of system are respectively discussed.

3.2.1 The operating temperature

When the mass flow of input fuel keeps constant, with the increase of the operating temperature of SOFC, both the fuel cell voltage and system exergy efficiency increase. And

then, the required air for cooling fuel cell stack will decrease as shown in Figure 5. In addition, due to the enhancement of cell stack activity, the system exergy loss reduces and the total system output power increases as shown in Figure 6. When the operating temperature is above 920°C, the voltage begins to decrease and system exergy losses increased. Therefore, in the practical situation, the system should operate in the proper temperature.

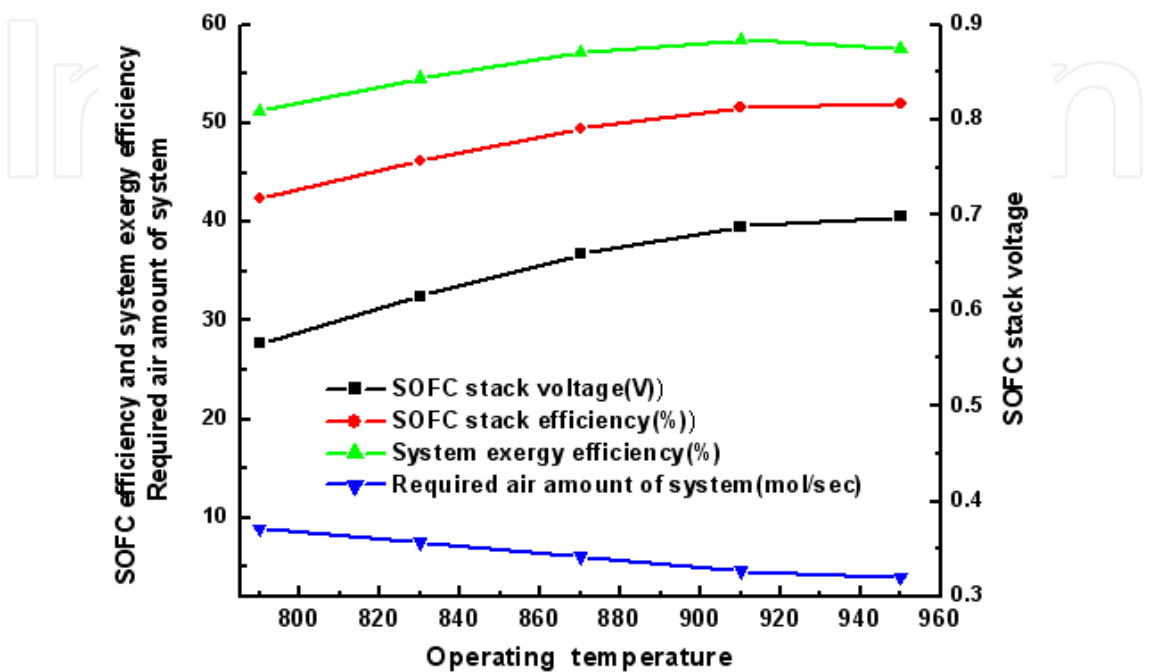


Fig. 5. The effect of operating temperature on system performance

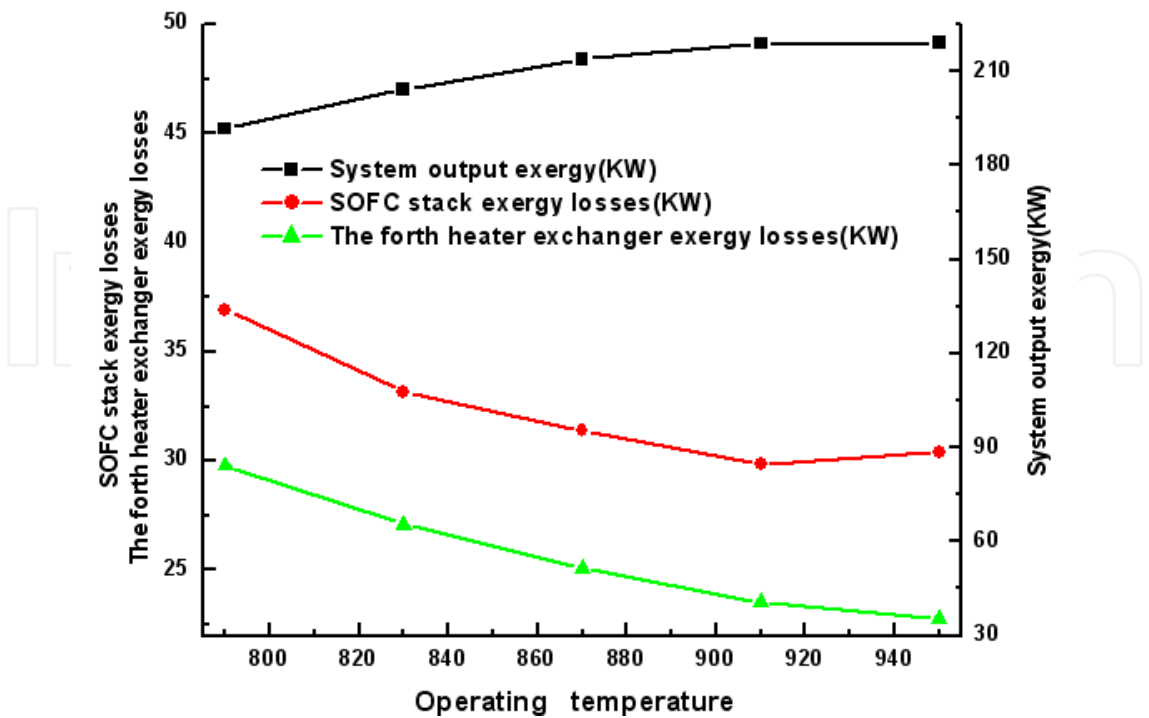


Fig. 6. The effect of operating temperature on system exergy parameters

3.2.2 The operating pressure

The operating pressure is vital to the system performance. Improving the operating pressure of SOFC stack, the SOFC voltage will increase because the H₂ amount in SOFC stack and H₂ partial pressure increase. Figure 7 shows that keeping the current density constant, with the increase of the operating pressure, the voltage increases. However, the growth rate gets smaller.

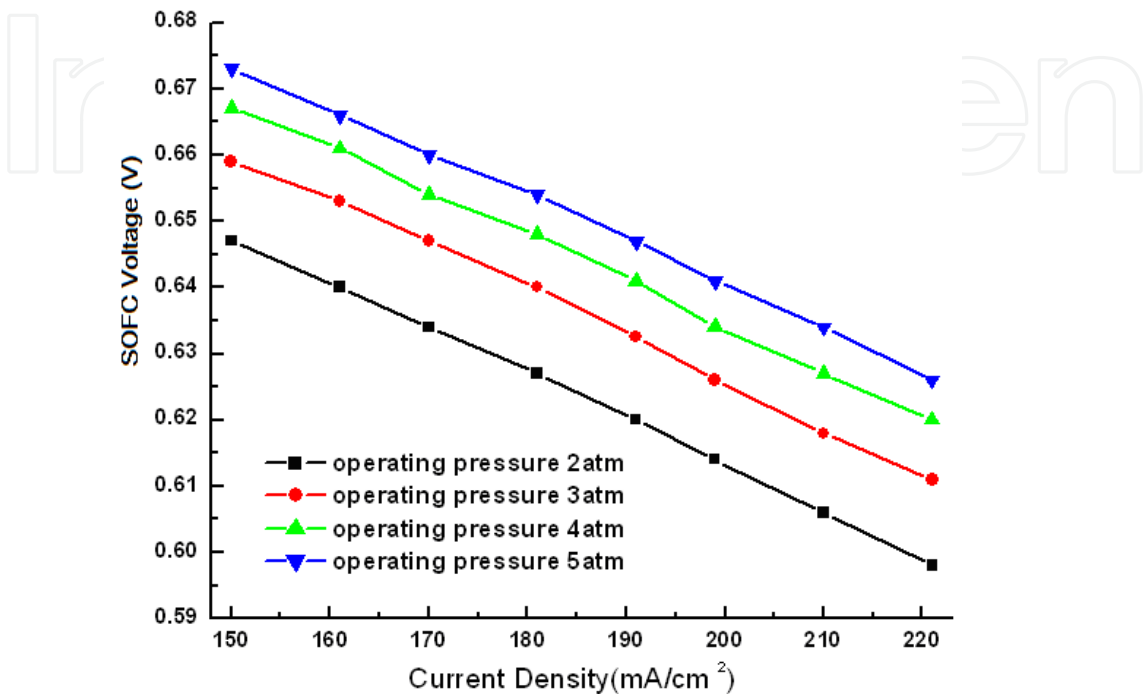


Fig. 7. The effect of operating pressure on SOFC Voltage

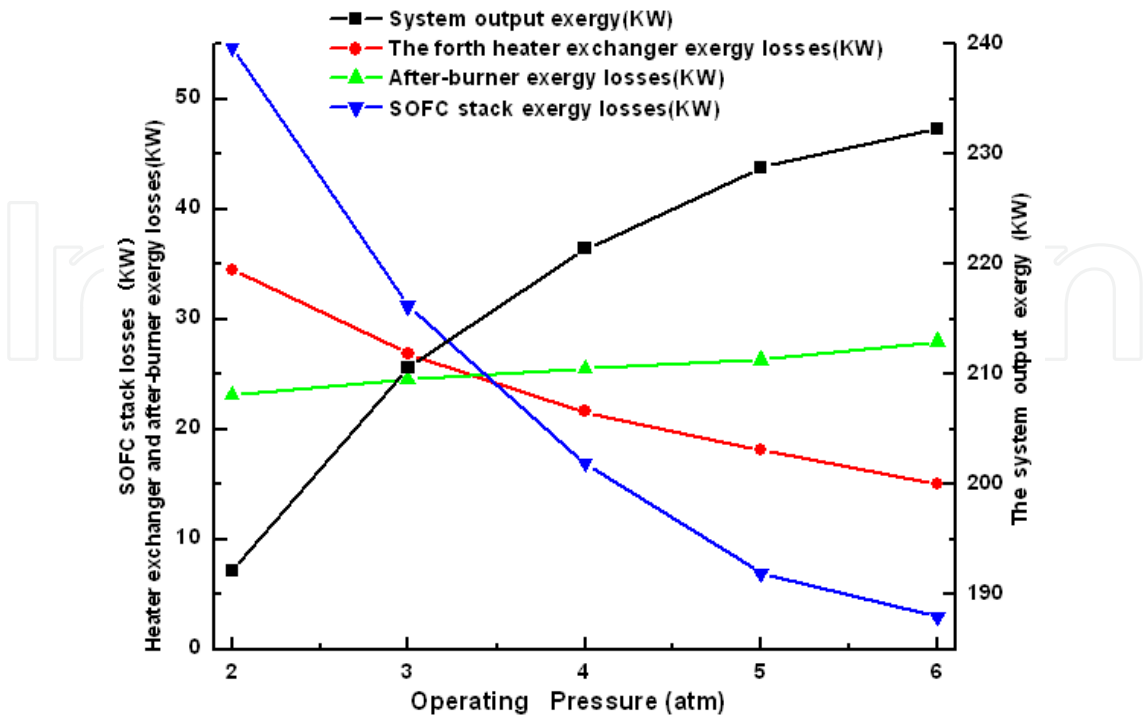


Fig. 8. The effect of operating pressure on system exergy performance

As shown in Figure 8, as the operating pressure increases, the SOFC stack exergy loss decreases and the total system output exergy increases. Because the required air for cooling fuel cell stack slowly increases, the after-burner exergy loss increases and the exergy loss of heat exchanger 4 decreases. In a word, the higher operating pressure is favorable to improving the performance of SOFC hybrid system. However, the higher pressure will increase the cost of system investment. Choosing the appropriate operating pressure should be taken into account when designing the SOFC.

3.2.3 The fuel utilization factor (U_f)

The fuel utilization factor (U_f) has a significant effect on the cell voltage and efficiency. As shown in Figure 9, with the increase of U_f from 0.7 to 0.9, the current density will increase, which will result in the decrease of the cell voltage. At lower values of U_f , when U_f increases, the cell voltage change is not significant, so the system output exergy will increase (as shown in Figure 10). But for higher U_f , the change amount of the cell voltage is bigger than that of the current density, as a result, the system exergy efficiency will reduce as shown in Figure 8. And U_f also has a significant impact on the composition of the anode exhaust stream. The CO_2 concentration at the anode outlet increases when U_f is increased because the fuel is more depleted (less CO and H_2), which will result in the change of the system unit exergy loss as shown in Figure 10.

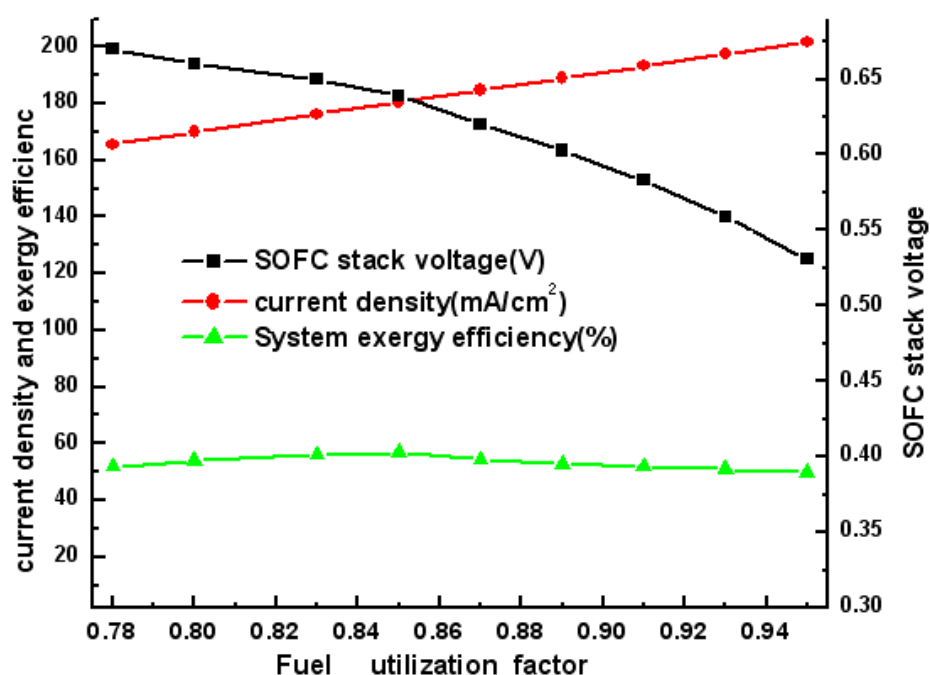


Fig. 9. The effect of fuel utilization factor on system performance

3.2.4 The cathode air input temperature

The cathode air consists of 79% nitrogen and 21% oxygen. As shown in Figure 11, with the increase of the cathode air input temperature, the activity of SOFC stack enhances. At the same time, both the required air for cooling fuel cell stack and the SOFC voltage increase, as a result, the system will produce more power. In addition, the inlet turbine gas temperature also increases, the power output of turbine will boost. But in order to meet the requirement

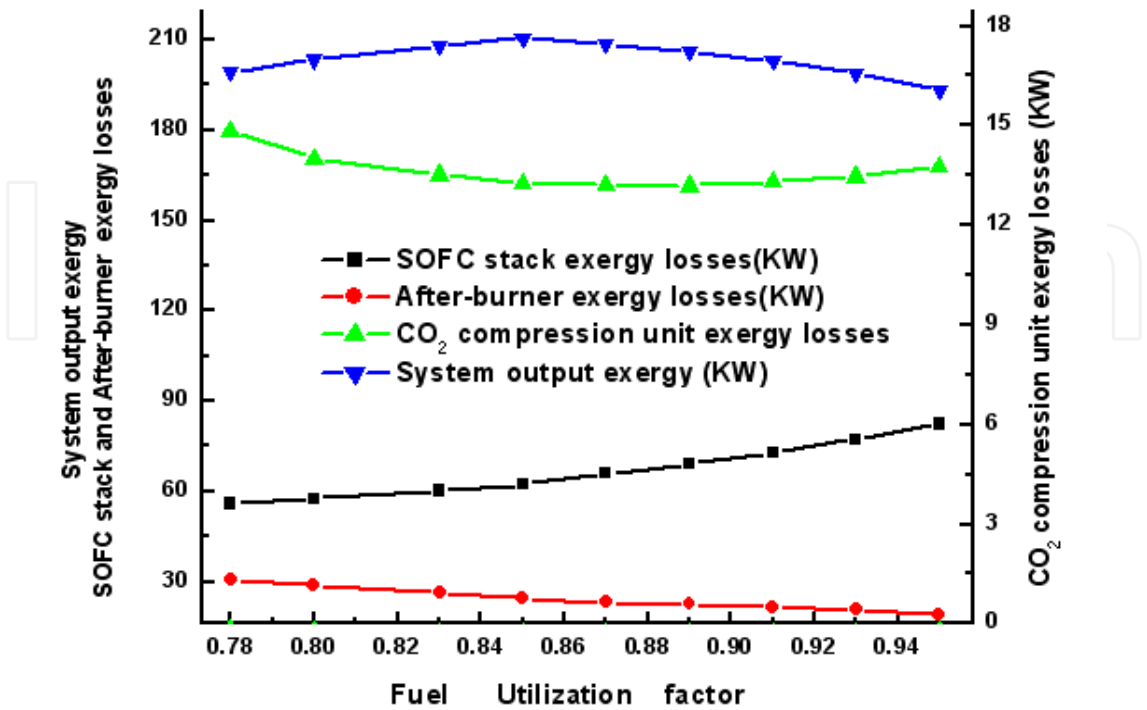


Fig. 10. The effect of fuel utilization factor on system exergy performance

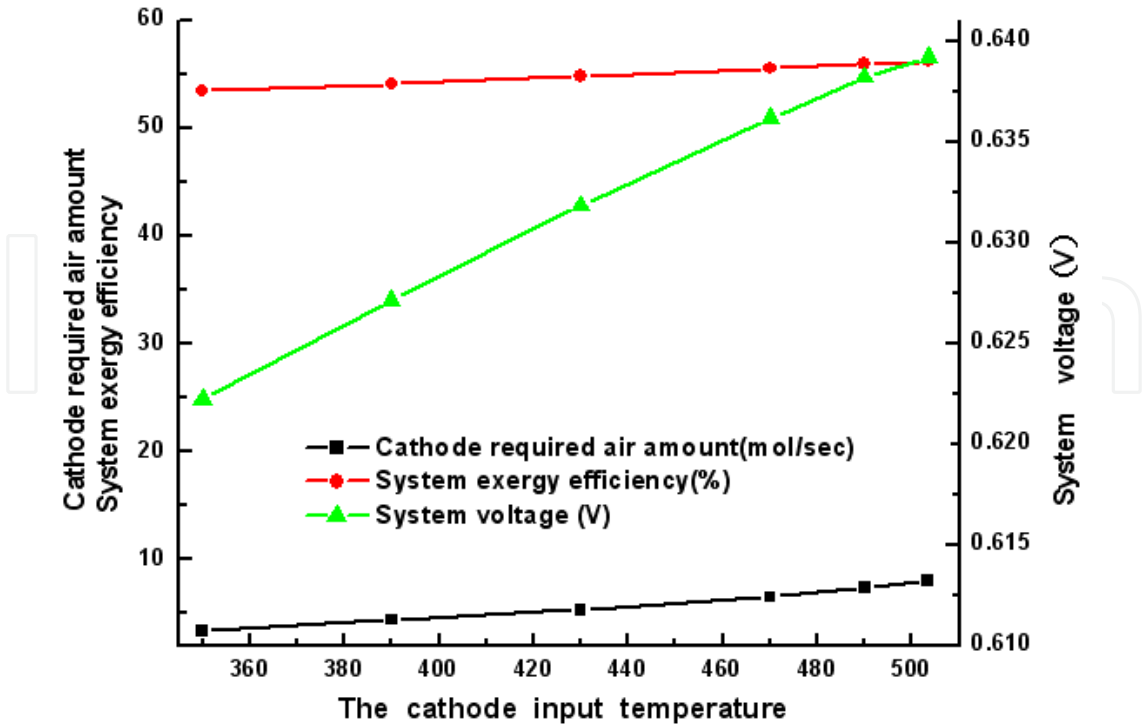


Fig. 11. The effect of cathode air input temperature on system performance

of the inlet air temperature, more heat of the exhaust gas will be consumed. The corresponding exergy loss of heat exchanger increases, so the system exergy efficiency isn't significant increased as shown in Figure 11. And as shown in Figure 12, the input temperature of cathode air also has an important effect on the other system performance parameters. The lower temperature will make the SOFC stack performance deteriorate.

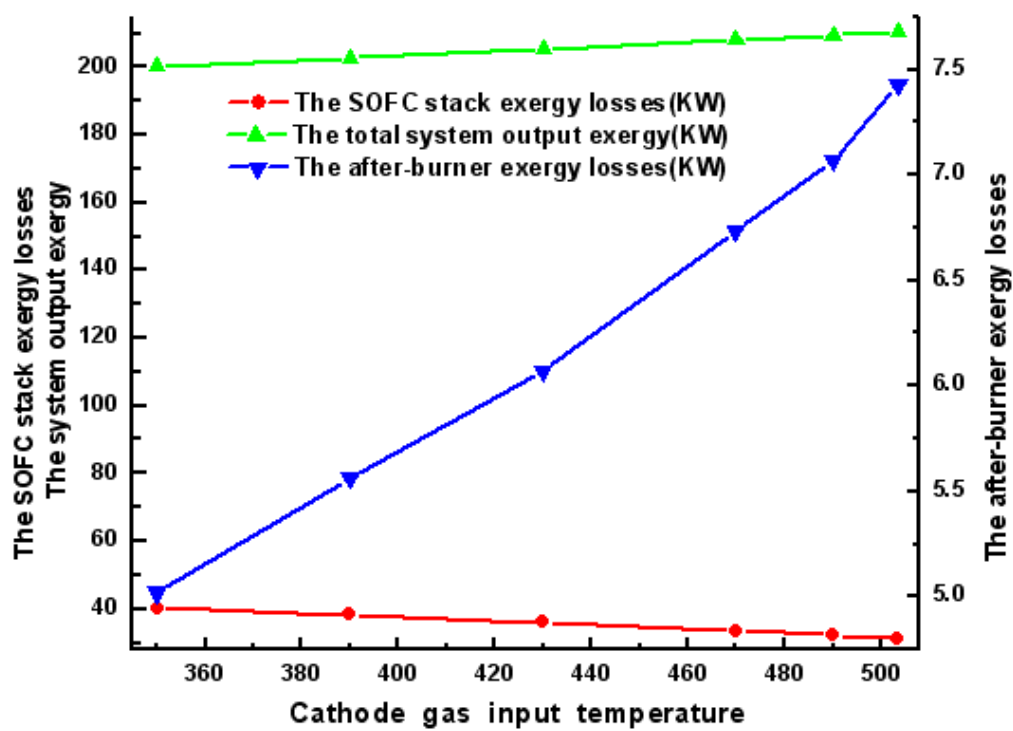


Fig. 12. The effect of cathode air input temperature on system exergy performance parameters

3.2.5 The oxygen concentration effect

As can be seen from Figure 13, when the operating pressure is a constant, as the oxygen purity increases, the O₂ partial pressure of SOFC stack cathode air improves, and this will make the system output exergy and exergy efficiency increase, especially SOFC stack with the lower operating pressure. Because the fuel flow remains unchanged, with the increase of oxygenconcentration, the required air decreases. Due to that the electrochemical reaction is exothermic reaction, it may cause the local area of stack overheat and the battery performance deteriorate. And with the increase of the oxygen concentration the consumed energy for separating the air will become bigger, so the exergy loss of the stack will rise slowly, which will result in the slow rise tend of system output exergy (as shown in Figure 14).

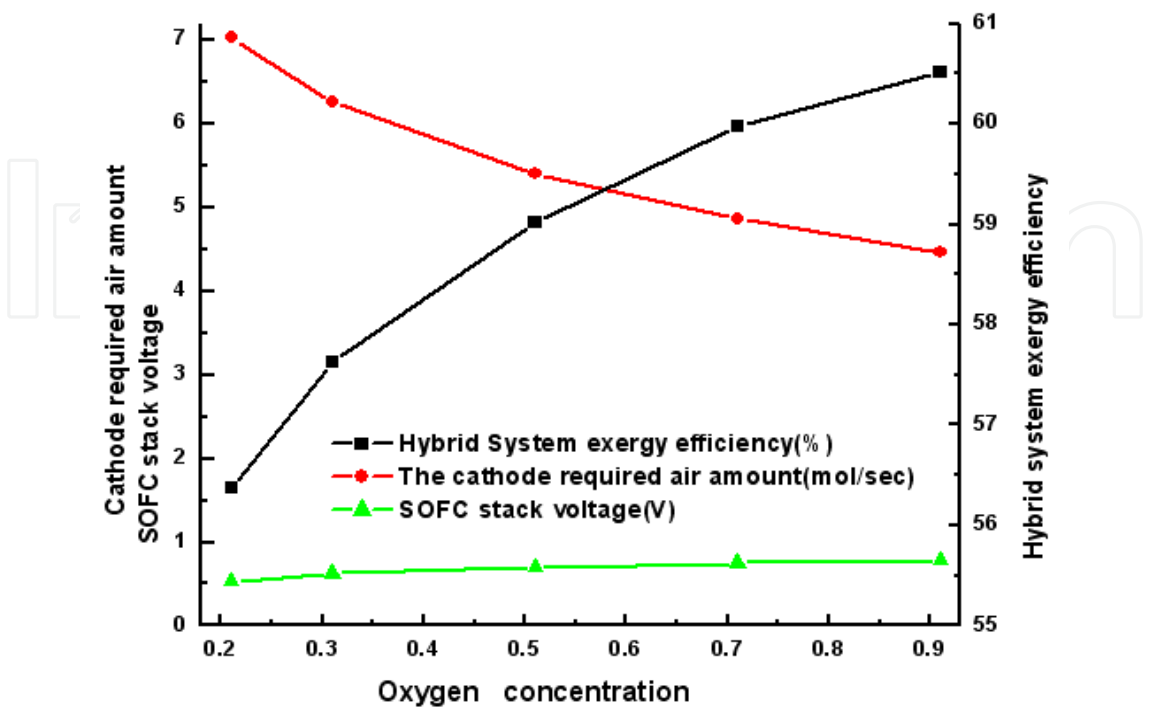


Fig. 13. The effect of oxygen concentration on system performance

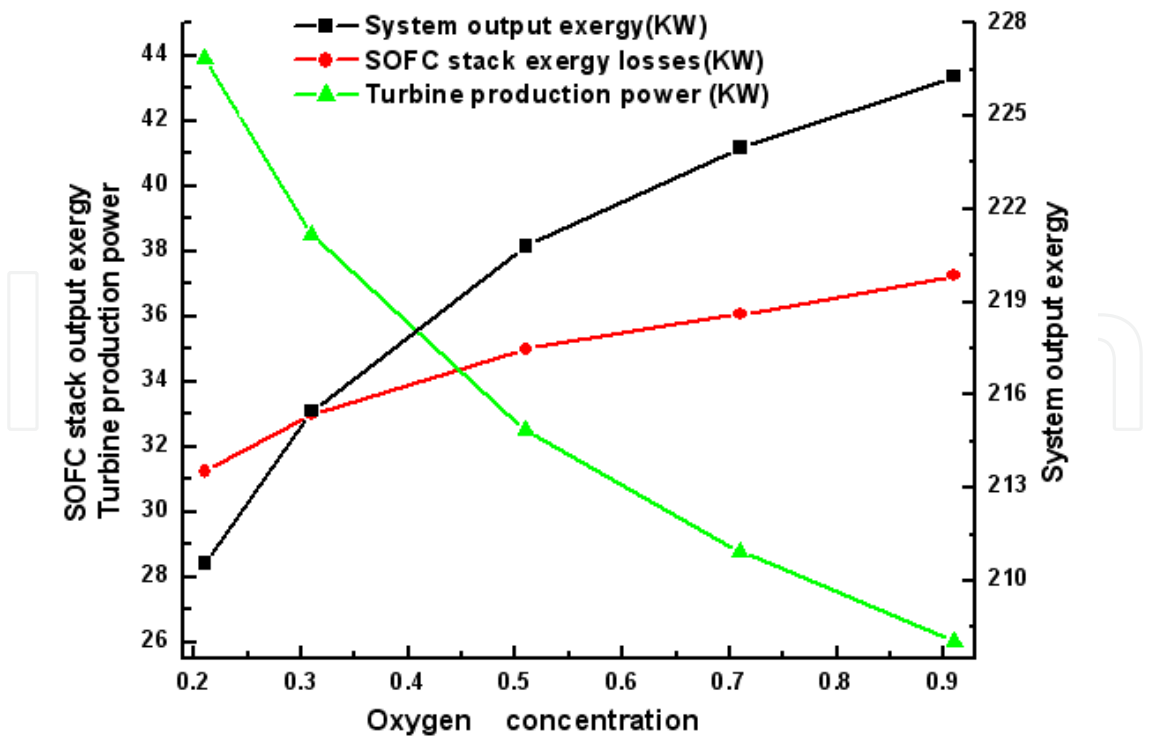


Fig. 14. The effect of oxygen concentration on system exergy performance

4. Conclusions

Based on a traditional SOFC (Solid Oxide Fuel Cell) hybrid power system, A SOFC hybrid power system with zero-CO₂ emission is proposed in this paper and its performance is analyzed. The exhaust gas from the anode of SOFC is burned with pure oxygen and the concentration of CO₂ gas is greatly increased. Because the combustion produce gas is only composed of CO₂ and H₂O, the separation of CO₂ hardly consume any energy. At the same time, in order to maintain the proper turbine inlet temperature, the steam produced from the waste heat boiler is injected into the afterburner, and then the efficiency of hybrid power system is greatly increased. With the exergy analysis method, this paper studied the exergy loss distribution of every unit of SOFC hybrid system with CO₂ capture and revealed the largest exergy loss unit. The effects of main operating parameters on the overall SOFC hybrid system with CO₂ capture are also investigated.

The research results show that the new zero-CO₂ emission SOFC hybrid system still has a higher efficiency. Its efficiency only decreases 3 percentage points compared with the basic SOFC hybrid system without CO₂ capture. The O₂/CO₂ combustion mode can fully burn the anode's fuel gas, and increase the concentration of CO₂ gas; at the same time with the steam injection and the combustion products are channeled into turbine, the efficiency of system greatly increases. The liquefaction of CO₂ by the mode of multi-stage compression and intermediate cooling can also greatly reduce the energy consumption.

The exergy analysis of the zero CO₂ emission SOFC hybrid power system shows that SOFC stack, after-burner and CO₂ compression unit are the bigger exergy loss components. By improving the input temperature of SOFC stack and turbine, the system exergy loss will significantly reduce. The optimal values of the operation parameters, such as operating pressure, operating temperature and fuel utilization factor exist, which make the system efficiency highest. Above research achievements will provide the new idea and method for further study on zero emission CO₂ system with higher efficiency.

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Gas turbine engines will still represent a key technology in the next 20-year energy scenarios, either in stand-alone applications or in combination with other power generation equipment. This book intends in fact to provide an updated picture as well as a perspective vision of some of the major improvements that characterize the gas turbine technology in different applications, from marine and aircraft propulsion to industrial and stationary power generation. Therefore, the target audience for it involves design, analyst, materials and maintenance engineers. Also manufacturers, researchers and scientists will benefit from the timely and accurate information provided in this volume. The book is organized into five main sections including 21 chapters overall: (I) Aero and Marine Gas Turbines, (II) Gas Turbine Systems, (III) Heat Transfer, (IV) Combustion and (V) Materials and Fabrication.

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