Study on coal-fired power plant with CO_2 capture by integrating molten carbonate fuel cell system

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Abstract:

In this paper a coal-fired power plant with CO_2 capture by integrating MCFC (molten carbonate fuel cell) system is studied. With the Aspen Plus software, the model of the hybrid system is proposed and the key parameters of MCFC are calculated, analyzed and optimized. The exhaust gas of the coal-fired power plant which contains about 14.74% CO_2 is mixed with the air before it is sent into the cathode of MCFC, CO_2 and O_2 are used as the reactant gas of MCFC cathode side. The carbonate ion (CO_3^{2-}) is generated with CO_2 and O_2 by an electrochemical reaction. Then the carbonate ion (CO_3^{2-}) of the cathode reacts with the fuel in the anode side, generating CO_2 and H_2O and producing power. The anode exhaust gas burns with the pure oxygen in the afterburner. The heat energy of the combustion production gas of the afterburner is adequately utilized by a series of heat exchangers and HRSG (heat recovery steam generator). The additional power is produced. The CO_2 in the exhaust gas of HRSG is further concentrated and captured with the lower energy consumption. The research results show that compared with the conventional coal-fired power plant without CO_2 capture, the efficiency of the new hybrid system is increased and the maximum CO_2 capture rate can be 96.21%. Compared with the conventional CO_2 capture technologies of coal-fired power plant, the CO_2 capture based the electrochemical method of MCFC proposed in this paper has the obvious advantages. While ensuring the high CO_2 capture rate, the total efficiency of the new hybrid system with CO_2 capture can be improved by 4.06 percent points. Achievements in this paper will provide the valuable reference for CO_2 capture of coal-fired power plant with low energy consumption.

Keywords:

MCFC, Coal-fired power plant, Hybrid system, CO_2 capture.

1. Introduction

Nowadays, with the rapid development of industry, the carbon dioxide emission which is the main cause of greenhouse effect and the sea-level rise has drawn the international community’s attention. The primary energy such as fossil energy is the main source of a large amount of CO_2 emission. About 70% of CO_2 emissions are from the coal-based power generation [1]. It’s a key issue to reduce CO_2 emissions of coal-based power plants in this new century. One way is to improve the efficiency of power generation and the other way is to apply the technology of CO_2 capture and recovery technology with low energy consumption. The post-combustion capture technology, oxygen-enriched combustion technology and pre-combustion capture technology are three main methods of CO_2 capture from the traditional power generation plant. The solvent absorption method [2-5], one of the post-combustion capture technologies, is mainly used in the coal-fired power plant which has high capture efficiency and selectivity. The pre-combustion capture technology [6-7] is mainly used in IGCC (integrated gasification combined cycle) system. The oxygen-enriched combustion technology [8-10] is a method that uses the pure O_2 mixed with part of flue gas instead of air for coal combustion to increase the concentration of CO_2 in flue gas.

The fuel cell power generation which is efficient, clean and safe has attracted a great attention of international society in recent years [11]. The chemical energy of the fuel in the anode of fuel cell can be converted into the electrical energy directly by an electrochemical process. Its power generation efficiency is not limited by the Carnot cycle, so it can have a higher efficiency than the conventional coal-fired power plant [12]. The coal-fired power plant has the largest, long-term and stable CO_2 emissions, so integrating MCFC with coal-fired power plant can increase the fuel utilization rate and system total efficiency, and reduce the energy consumption of capturing CO_2 from the exhaust gas of boiler, which has a great potential of energy conservation.

In recent years, many researchers have carried out related researches on MCFC and MCFC hybrid system with CO_2 capture. Amorelli [13] made an experiment on CO_2 capture from the exhaust gas of gas turbine with MCFC and the result showed that the MCFC can operate at sub-optimal CO_2 levels with the limited loss in power and efficiency. Chiesa [14] investigated an advanced cycle with the limited CO_2 emission based on the integration of molten carbonate fuel cells in a natural gas fired combined cycle power plant in order to capture CO_2 from the exhaust of the gas turbine. The result showed that the carbon capture ratio was 80% and the final electric efficiency was about the same as that of the original combined cycle system. The output power increased about 22%, giving a potentially relevant advantage with respect to competitive carbon capture technologies. Spallina [15] investigated the IGCC by integrating a MCFC system for CO_2 capture. The result showed that the efficiencies of the IGFC (integrated gasification fuel cell cycle) were 46.0-47.1%, 0.1-1.25% points less than the reference IGCC cycle, while achieving 58-91% lower specific CO_2 emissions. This concept could be competitive when plant economics and the cost of CO_2 avoided were considered. Campanari [16] investigated the conventional power plant integrated with MCFC system for CO_2 separation. The result showed that about 80% of the total CO_2 emission was contained by the MCFC anode exhaust, leaving the remaining 20% in the diluted MCFC cathode exhaust gas. The overall efficiency including the MCFC output and gas treatment energy consumption increased from the original 45% of the simple steam power plant to 45.8% of the new plant, bringing about a substantial (40%) increase in the power output. Desideri [17] investigated the chemical composition of flue gases from existing cogeneration plants by developing a model of a MCFC used as input the exhaust gas of a combined heat and power plant. The result showed that the maximum achievable CO_2 removal efficiency was 98.7%, and at this point the choice of the best combination depended only on the value assumed by the electrical efficiency of the cell.

On the basis of the above researches, this paper studies a coal-fired power plant with CO_2 capture by integrating the MCFC system. The model of the hybrid system which is integrated with MCFC, air separation unit and CO_2 capture and recovery unit is established with the Aspen plus [18] software and the important parameters are simulated and analyzed. The coal-fired power plant without CO_2 capture is used as the benchmark system. The exhaust gas of coal-fired power plant is sent into the cathode of MCFC to provide CO_2 for the electrochemical reaction in order to achieve the low CO_2 emissions. This MCFC hybrid system can be used to solve the problems of the low efficiency of coal-fired power plant and a large amount of CO_2 emissions. Achievements in this paper will provide the valuable reference for CO_2 capture of coal-fired power plant with low energy consumption.

2. System description

2.1. Coal-fired power plant system without CO_2 capture

The coal-fired power plant mainly uses a reheat cycle unit with multi-stage feeding water heaters. In this paper, a coal-fired power plant system without CO_2 capture shown in Fig. 1 is taken as the benchmark system, which is a single-shaft arrangement with double LP turbines and eight-stage feeding water heaters. The pulverized coal mixed with the hot air burns in the boiler with the high temperature flue gas heating the feed water into the saturated steam and the superheated steam. The high temperature flue gas flows through the economizer and air preheater heating the low temperature feed water and air, then the low temperature flue gas flows into the gas treatment equipment to remove SO_2 and ash, and exhausts into the atmosphere eventually. The composition of the exhaust gas mainly contains CO_2, N_2, O_2 and Ar. The high temperature steam out from the boiler produces power by expanding in HP turbine. Part of the outlet steam heats the high-pressure heater II and the rest produces power by expanding in IP turbine after reheated in the boiler. The outlet steam of IP turbine flows into LP turbine to produce power and mixes with the condensate in the condenser. Then, the condensate is sent into the low-pressure feed water heaters by a condensate pump. The feeding water flows through the deaerator and high-pressure heaters, raised to about 271°C and back to the boiler. The generator produces the electricity drived by turbines rotating in a high speed. Finally, the exhaust gas temperature out of the coal-fired power plant is about 129°C.

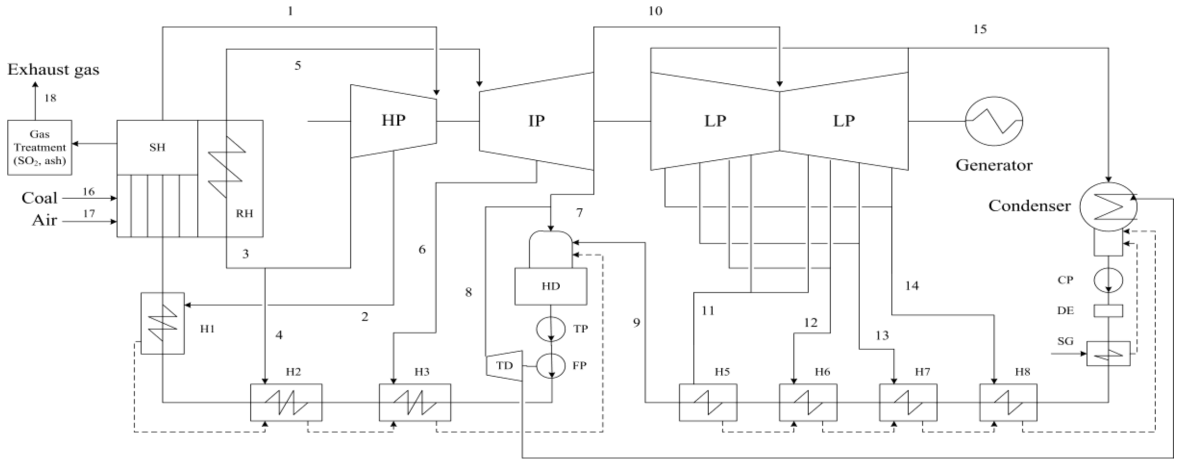


Fig. 1. Flowchart of coal-fired power plant without CO_2 capture (benchmark system).

2.2. Coal-fired power plant with CO_2 capture by integrating MCFC system

The flowchart of coal-fired power plant with CO_2 capture by integrating MCFC system is shown in Fig. 2. The exhaust gas 1 of the coal-fired power plant which contains about 14.74% CO_2 mixed with air 1 enters into the cathode of MCFC after heated by the high temperature exhaust gas 2 of the cathode of MCFC. The CO_2 and O_2 in the mixed gas generate the carbonate ion (CO_3^{2-}) by an electrochemical reaction in the cathode side and the rest mixed gas is exhausted by the cathode of MCFC. The mole ratio of CO_2 to O_2 is 2.0. The fuel 1 is mixed with part of the anode exhaust gas and produces H_2 and CO in the pre-reformer unit. The electrochemical reaction of the mixture gas of the pre-reformer and the carbonate ion (CO_3^{2-}) of the cathode takes place in the anode, CO_2 and H_2O are generated. At the same time the DC (direct current) is generated and converted into the AC (alternative current) by a DC/AC converter. The anode exhaust gas is divided into two parts to meet the specific ratio (2.5) of S/C (steam to carbon) in the stream 2 and to prevent the carbon deposition phenomenon in the pre-reformer. About 67.5% of the anode exhaust gas is recycled to the pre-reformer to heat the fuel gas and the rest is sent to the afterburner to burn with pure O_2 provided by the air separation unit (ASU). The high temperature exhaust gas of the afterburner is cooled to an appropriate temperature (about 650°C) by part of the exhaust gas of the heat recovery steam generator (HRSG) and sent to the HRSG and steam turbine system to produce additional power. After the utilization of waste heat by the HRSG, the exhaust gas of the HRSG contains only H_2O and CO_2. Part of the exhaust gas is sent back to the afterburner to cool the exhaust gas of the afterburner and the rest is sent to the CO_2 compression and recovery unit. The liquid CO_2 with high purity is produced by a three-stage CO_2 compression and recovery unit.

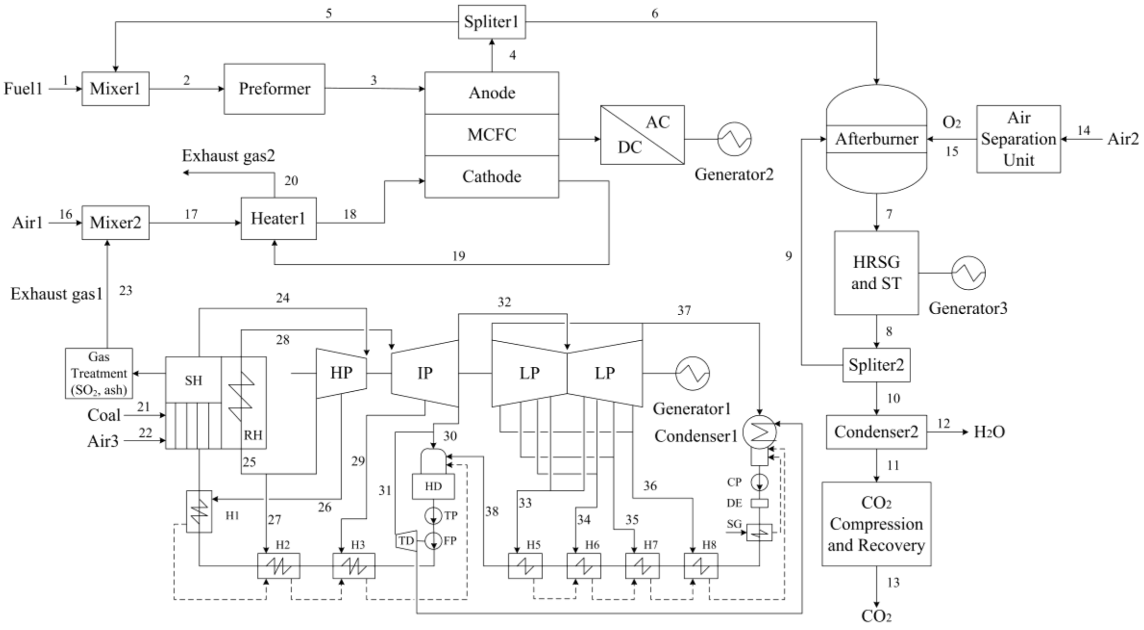


Fig. 2. Flowchart of coal-fired power plant with CO_2 capture by integrating MCFC system.

3. MCFC system model

The operating temperature of MCFC is about 650°C. In this paper the main fuel composition of MCFC is CH_4. CH_4 and H_2O of the anode exhaust gas react in the pre-reformer, providing H_2 for the anode of MCFC. The main reactions occurred in MCFC are as follows:

Reforming reaction:

$$CH_4 + H_2O = CO + 3H_2 \tag{1}$$

$$CO + H_2O = CO_2 + H_2 \tag{2}$$

Cathode reaction:

$$O_2 + 2CO_2 + 4e^- = 2CO_3^{2-} \tag{3}$$

Anode reaction:

$$H_2 + CO_3^{2-} = H_2O + CO_2 + 2e^- \tag{4}$$

The ideal reversible voltage of MCFC is calculated by the Nernst equation (E_{Nernst}) [19]:

$$E_{Nernst} = \frac{\Delta G}{nF} + \frac{RT}{nF} ln\left[\frac{P_{H_2,an}\left(P_{O_2,an}\right)^{\frac{1}{2}} P_{CO_2,ca}}{P_{H_2O,an} \cdot P_{CO_2,an}}\right] \tag{5}$$

The Gibbs free energy (ΔG) changes with the operating temperature (T), which is calculated by the equation as follows [19]:

$$\Delta G = 242000 - 45.8 \times T \tag{6}$$

The current of MCFC (I) is related to the electron numbers transferred in electrochemical reactions. The equations of the current and the current density (i_c) are as follows:

$$I = \frac{znF}{N} \tag{7}$$

$$i_c = \frac{I}{A} \tag{8}$$

When the actual voltage is calculated, the voltage loss caused by the irreversible polarization losses should be considered. The polarization losses contain the ohm polarization, activation polarization and concentration polarization. All three polarization losses increase with the increase of the current density. The actual voltage of MCFC (V_c) is calculated by the following equations [19]:

$$V_c = E_{Nernst} - \left(R_{an} + R_{ca} + R_{ohm}\right) \cdot i_c \tag{9}$$

$$R_{an} = 2.27 \times 10^{-9} \times exp\left(\frac{E_{act,an}}{RT}\right) \cdot P_{H_2}{}^{-0.43} \cdot P_{CO_2}{}^{-0.17} \cdot P_{H_2O}{}^{-10} \tag{10}$$

$$R_{ca} = 7.505 \times 10^{-10} \times exp\left(\frac{E_{act,ca}}{RT}\right) \cdot P_{O_2}{}^{-0.43} \cdot P_{CO_2}{}^{-0.09} \tag{11}$$

$$R_{ohm} = 0.5 \times 10^{-4} \times exp\left[3016\left(\frac{1}{T} - \frac{1}{923}\right)\right] \tag{12}$$

The output power of MCFC:

$$W_{MCFC} = \alpha \times V_c \times I \tag{13}$$

4. System performance evaluation

In this paper the main performance evaluations of the coal-fired power plant with CO_2 capture by integrating MCFC system are CO_2 utilization rate (U_{CO_2}), fuel utilization rate (U_f), CO_2 capture rate (σ) and system total efficiency (η). CO_2 utilization rate (U_{CO_2}) is defined as the ratio of the CO_2 reacted in the anode ($CO_{2out,ca}$) to the total CO_2 in the cathode ($CO_{2in,ca}$). It can be calculated as follows:

$$U_{CO_2} = \left(1 - \frac{CO_{2out,ca}}{CO_{2in,ca}}\right) \times 100\% \tag{14}$$

Fuel utilization rate (U_f) of MCFC which represents the mole fraction of the fuel takes part in the electrochemical reaction is defined as:

$$U_f = \left(1 - \frac{fuel_{out,an}}{fuel_{in,an}}\right) \times 100\% \tag{15}$$

CO_2 capture rate (σ) is defined as the ratio of the captured CO_2 ($CO_{2capture}$) to the total CO_2 contained in the new hybrid system (CO_{2total}). It is calculated according to the following equation:

$$\sigma = \frac{CO_{2capture}}{CO_{2total}} \times 100\% \tag{16}$$

System total efficiency (η) is the ratio of the net total output power to the system total input energy. The equation is as follows:

$$\eta = \frac{W_{CFPP} + W_{MCFC} + W_{HRSG} - W_{ASU} - W_{CO_2COMP}}{G_{CFPP} \times LHV_{coal} + G_{MCFC} \times LHV_{CH_4}} \times 100\% \tag{17}$$

5. Results and discussions

To ensure the efficient comparison between different systems, in this paper the new hybrid system (coal-fired power plant with CO_2 capture by integrating MCFC) and the benchmark system (coal-fired power plant without CO_2 capture) are based on the same simulation parameters and assumptions. The main simulation parameters are shown in Table 1 and Table 2.

Table 1. Coal composition.

Mass fraction(%)							LHV(kJ/kg)
C	H	O	N	S	ash	moisture	21981
57.5	3.11	0.99	2.78	2.02	23.7	9.9	

Table 2. Main simulation parameters.

Ambient condition	25°C, 1atm
Air composition	N_2 78%, O_2 21%, CO_2 0.03%, H_2O 0.03%, Ar 0.94%
Coal-fired power plant	
Feed water mass flow and temperature	466kg/s, 271°C
Coal mass flow	65.86kg/s
Air mass flow	608kg/s
Superheated steam mass flow, temperature and pressure	1677.6t/h, 566°C, 24.2MPa
Reheated steam mass flow, temperature and pressure	1400.4t/h, 566°C, 4.05MPa
Boiler exhaust gas mass flow and temperature	660.3kg/s, 129°C
Condenser pressure	5.88kPa
Generator output power	600MW
MCFC	
Cell reaction temperature	650°C
Cell operating pressure	1atm
Fuel composition	CH_4 100%
Lower heating value of fuel	50030kJ/kg
Steam-to-carbon ratio	2.5
Cell current density	1500A/m^2
Heat loss to environment	2%
Fuel utilization rate	85%
CO_2 utilization rate	85%
Air separation unit	
Air mass flow	32.7kg/s
Air compressor operating pressure	0.6MPa
O_2 pressure	0.105MPa
HRSG	
Pressure levels of HP/IP/LP turbine	16.5MPa/3.6MPa/0.39MPa
Mechanical efficiency of turbine	99%
Isentropic efficiency of HP/IP/LP turbine	90%/91%/92%
Superheated/reheated steam temperature	565°C/565°C
Exhaust gas temperature	109.6°C
CO_2 compression and recovery	
Compression stage	3
Outlet temperature	30°C
Outlet pressure	80atm

The composition of the exhaust gas of the coal-fired power plant is 14.74% CO_2, 82.7% N_2, 1.95% O_2 and 0.61% Ar. Table 3 shows the comparison results between the benchmark system and the new hybrid system. It can be seen that the efficiency of the benchmark system is 41.57%. When the CO_2 utilization rate is 65%, the efficiency of MCFC is 54.64% and the total efficiency of the new hybrid system with CO_2 capture is 45.49%, which is 3.92 percent points higher than that of the benchmark system. The CO_2 capture rate is 70.64%. The net output power of the new hybrid system is 867.75MW, which is 265.95MW higher than that of the benchmark system. It shows that compared with the benchmark system, both the net output power and the system total efficiency of the new hybrid system are higher. When the CO_2 utilization rate is 85%, the system total efficiency of the new hybrid system is 45.63%, 4.06 percent points higher than that of the benchmark system and 0.14 percent points higher than that of the new hybrid system when the CO_2 utilization rate is 65%. The CO_2 capture rate is 88.07%, which is 17.43 percent points higher than that when the CO_2 utilization rate is 65%. The MCFC and HRSG produce the additional power which is higher than that ASU and CO_2 compression unit consume. As a result, the net output power of the new hybrid system is 935.32MW, 333.52MW higher than that of the benchmark system.

The waste heat can be used to produce the additional power adequately by sending the high temperature exhaust gas of the afterburner to the HRSG. With this method, the exergy loss of the new hybrid system is reduced and the system total efficiency is increased. Since the pure O_2 is provided for the afterburner, the combustion product gas mainly contains CO_2 and H_2O. The energy consumption is greatly reduced during the CO_2 compression and recovery without N_2 in the exhaust gas. When the CO_2 utilization rate is 85%, the CO_2 mole fraction in the exhaust gas of the new hybrid system is reduced from 14.74% to 1.66% compared with the benchmark system. It can be seen that most CO_2 of coal-fired power plant exhaust gas is recycled by the new hybrid system. Moreover, the net output power and the total efficiency are greatly improved. The coal-fired power plant with CO_2 capture by integrating MCFC system has a significant performance advantage. But this MCFC system with high net output power requires a huge MCFC stack area. In this paper the MCFC stack area simulated is about 328210m^2. In addition, though there are difficulties to establish this MCFC system with the high net output power more than 250MW with the current technology, with the development of MCFC technology that will not be a problem in the future.

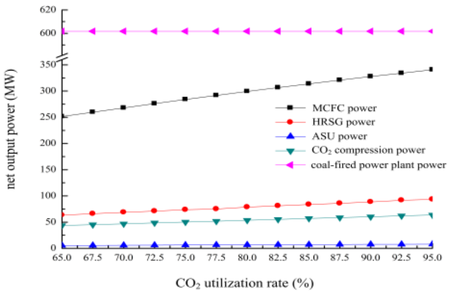
Table 3. Simulation results of the benchmark system and new hybrid system.

	The benchmark system	New hybrid system (CO_2 utilization rate is 65%)	New hybrid system (CO_2 utilization rate is 85%)
Coal mass flow, kg/s	65.86	65.86	65.86
CFPP power, MW	601.8	601.8	601.8
CFPP efficiency, %	41.57	41.57	41.57
MCFC fuel mass flow, kg/s	-	9.20	12.03
MCFC power, MW	-	251.40	313.89
MCFC efficiency, %	-	54.64	52.14
MCFC voltage, V	-	0.704	0.671
HRSG power, MW	-	63.43	83.60
Air mass flow of ASU, kg/s	-	24.99	32.70
Power consumption of ASU, MW	-	5.45	7.13
Power consumption of CO_2 compression, MW	-	43.47	56.89
Net total output power, MW	601.8	867.75	935.32
Total efficiency, %	41.57	45.49	45.63
CO_2 capture rate, %	-	70.64	88.07

5.1. Influence of the CO_2 utilization rate

The CO_2 capture rate (σ) is an important evaluation indicator of the new hybrid system, while the CO_2 utilization rate (U_{CO_2}) is one of the important parameters that influence σ. This paper analyzes the effect of U_{CO_2} on the system total efficiency in the case of the same assumptions such as the fuel utilazation rate and the current density.

Fig. 3 shows that the net output power of every unit is increased while U_{CO_2} increases. The fuel that MCFC needs increases with the increase of U_{CO_2}. As a result, the exhaust gas mass flow of MCFC anode side increases, and the net output power of every unit is increased. The exhaust gas of the coal-fired power plant is constant, so the mass flow of CO_2 in the cathode is constant. The CO_2 that takes part in the electrochemical reaction is increased with the increase of U_{CO_2}, so the fuel that MCFC needs is increased as shown in Fig. 4. With the constant fuel utilization rate (U_f), the MCFC efficiency is decreased. Fig. 5 shows that the net output power increases because the ratio of the MCFC net output power to the net output power is higher and the growth rate is higher. As for the new hybrid system, the MCFC efficiency is higher than that of the benchmark system, the input energy of MCFC is lower than that of benchmark system with the low U_{CO_2}. With the increase U_{CO_2}, the input energy of MCFC is higher, the ratio of the fuel that MCFC needs to the total fuel becomes higher with the increase of U_{CO_2}, and the growth rate of total fuel is higher than that of net total output power. So the system total efficiency increases at first and then decreases. Fig. 6 shows that the σ rises while the U_{CO_2} increases. The σ can be risen to 96.21% when the U_{CO_2} is 95%, but in this condition the total efficiency is lower than other conditions. In order to reach a high total efficiency while the hybrid system also has the high σ and high net output power, in this paper the variation rules of the other parameters are analyzed under the condition that U_{CO_2} is 85%.



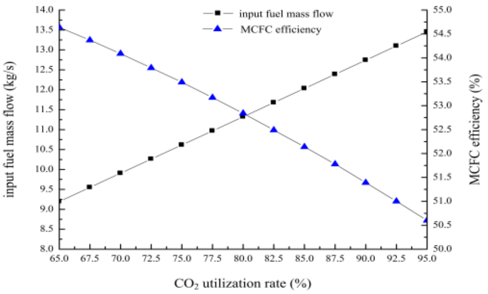
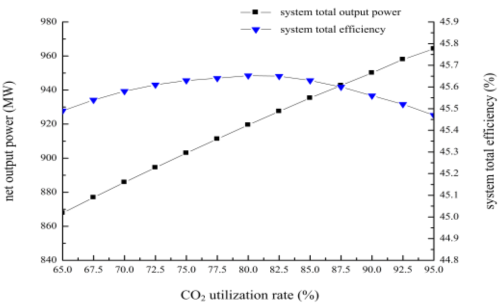


Fig. 3. Effect of CO_2 utilization rate on the power of various subsystems.

Fig. 4. Effects of CO_2 utilization rate on the MCFC input fuel mass flow and MCFC efficiency.



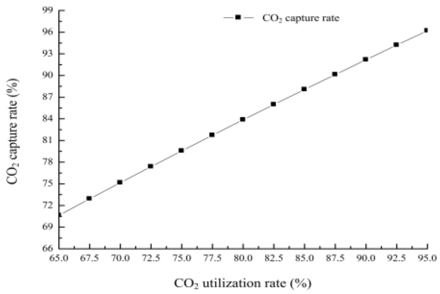


Fig. 5. Effects of CO_2 utilization rate on the system total output power and system total efficiency.

Fig. 6. Effect of CO_2 utilization rate on CO_2 capture rate.

5.2. Influence of the fuel utilization rate of MCFC

Since the exhaust gas mass flow of coal-fired power plant and the U_{CO_2} are constant, the fuel that the anode of MCFC consumed reduces with the increase of the fuel utilization rate (U_f). As shown in the Fig. 7, both the current density of MCFC and the polarization loss increase which will cause the drop of the cell voltage. In order to obtain a high cell voltage, the U_f should be as low as possible. But the lower U_f not only means that the fuel is not consumed well but also the internal friction of cell increases [20]. In this paper, the U_f is set as 85% during the simulation. Fig. 8 shows that while the mass flow of CO_2 in the cathode and U_{CO_2} stay unchanged, the fuel that the MCFC anode consumed reduces with the increase of the U_f, so the H_2 provided by the fuel decreases and the net output power of MCFC decreases. The effect of U_f on the mass flow of fuel is greater than that on the net output power of MCFC, so the system total efficiency rises firstly and then decreases. Since the H_2 provided by the fuel decreases, the CO_2 reacted in the anode decreases which causes the decrease of the CO_2 capture rate (σ).

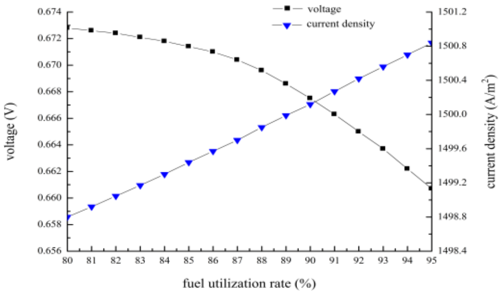


Fig. 7. Effects of fuel utilization rate on the MCFC voltage and current density.

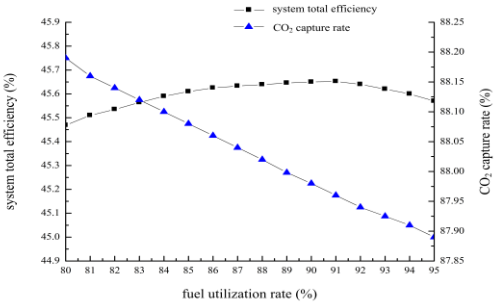


Fig. 8. Effects of fuel utilization rate on the system total efficiency and CO_2 capture rate.

5.3. Influence of the current density

The current density is another important parameter of the cell. Fig. 9 shows that when the parameters such as the U_{CO_2}, U_f and the mass flow of exhaust gas in the coal-fired power plant stay constant, with the increase of the current density, the cell voltage decreases because the cell internal resistance increases and the reaction activity reduces. As shown in Fig. 10, when the fuel of the anode and the current of the cell keep in constant, the net output power of MCFC, the MCFC efficiency and the system total efficiency all decrease. In order to ensure the normal operating voltage and high efficiency, in this paper the current density is set as 1500A/m^2 when the other parameters are analyzed.

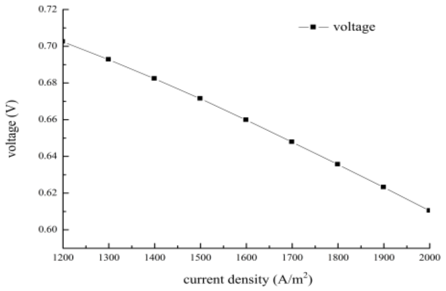


Fig. 9. Effect of current density on the MCFC voltage.

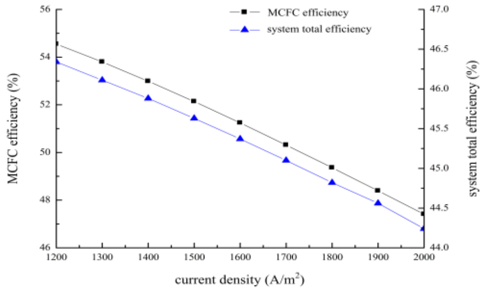


Fig. 10. Effects of current density on the MCFC efficiency and system total efficiency.

It can be seen from Fig. 5, Fig. 8 and Fig. 10 that the CO_2 utilization rate, fuel utilization rate and current density all make significant influences on the system total efficiency. With the increase of U_{CO_2} and U_f, the system total efficiency rises firstly and then reduces. The system total efficiency decreases with the increase of the current density. Among the above three parameters, the effect of the current density on the system total efficiency is most remarkable, while the CO_2 utilization rate has the least remarkable effect on the system total efficiency. In order to ensure the normal operating and high efficiency, in this paper the current density is set as 1500A/m^2, the U_{CO_2} is set as 85% and the U_f is set as 85%. During the simulation of the new system, the proper parameters of the CO_2 utilization rate, the fuel utilization rate and the current density should be selected to meet the optimum performance of the new hybrid system.

6. Conclusions

In order to solve the problem of environmental pollution caused by a large amount of CO_2 emission from the coal-fired power plant, this paper proposed a coal-fired power plant with CO_2 capture by integrating MCFC system. Aspen Plus simulation software is used to establish the system model and analyze the new hybrid system performance under different parameter conditions compared with the benchmark system of coal-fired power plant without CO_2 capture. The total CO_2 in the new system contains the CO_2 in the exhaust gas of the coal-fired power plant and the total CO_2 generated in the MCFC. The result shows that compared with the efficiency of the coal-fired power plant without CO_2 capture system (41.57%), when the CO_2 utilization rate is 65%, the total efficiency of the new hybrid system (45.49%) increases 3.92 percent points and the CO_2 capture rate is 70.64%. When the CO_2 utilization rate is 85%, the total efficiency of the new hybrid system (45.63%) increases 4.06 percent points and the CO2 capture rate is 88.07%. It can be seen from the sensitivity analysis that the CO_2 capture rate rises with the increase of the CO_2 utilization rate and reduces with the increase of the fuel utilization rate.

Nomenclature

A	cell active area, m^2
CFPP	coal-fired power plant
$E_{act,an}$	activation exergy of anode, 3500kJ/kmol
$E_{act,ca}$	activation exergy of cathode, 77229kJ/kmol
F	Faraday constant, 96487C/mol
G_i	mass flow rate of i stream, kg/s
LHV	lower heating value, kJ/kg
n	electronic number released in dissociation of a H_2 molecule (equal to 2)
N	number of unit cell
P_k	partial pressure of k component, atm
R	molar gas constant
R_i	cell resistance
W_i	output power of i unit, MW
z	mole flow rate of reacted H_2, mol/s

Greek symbols

α	DC-AC efficiency
σ	CO_2 capture rate
η	total efficiency

Subscripts and superscripts

act	activation
an	anode
ca	cathode
ohm	ohmic polarization

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