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A novel IGCC system with steam injected H_2/O_2 cycle and CO_2 recovery

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Abstract

In this paper, we have proposed a novel integrated gasification combined cycle (IGCC) system with steam injected H_2/O_2 cycle and CO_2 recovery. A new evaluation criterion for comprehensive performance of the IGCC system has also been presented. The thermodynamic characteristics, environmental and comprehensive performance of the new system have been investigated based on comparison of different IGCC systems with O_2/CO_2 cycle. The promising results show the new system has less energy penalty for separating and recovering CO_2, an efficiency decrease of less than 1 percentage point. The ratio of CO_2 penalty price to fuel price is an important factor influencing the comprehensive performance of this system. The performance of the IGCC with O_2/CO_2 cycle and syngas separation is better than that with the simple semi-closed O_2/CO_2 cycle. The above research achievements will provide valuable information for further study on IGCC systems with low CO_2 emission.

Keywords: H_2/O_2 cycle; Steam injection; IGCC; CO_2 recovery

1. Introduction

The integrated gasification combined cycle (IGCC) is one of the advanced clean coal power generation systems. Compared with the conventional coal fired power plant, it has lower emissions of SO_2, NO_X and particle pollutants. Though it is reputed to be the cleanest coal fired power plant, CO_2 emission cannot be greatly reduced by this technology and only proportionally reduced with improvement of the IGCC system efficiency. So, how to reduce CO_2 emission effectively from the IGCC system becomes the main subject of researchers [1–10].

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Nomenclature

b	fuel consumption ratio, kg/kWh
C_E	fuel price, $/kg
C_P	CO_2 penalty price, $/kg
G_{cl}	mass flow of fuel consumption, kg/s
G_{CO_2}	CO_2 specific emission, kg/kWh
G_{CO_20}	CO_2 specific emission from system without CO_2 recovery, kg/kWh
G_S	mass flow of steam injected to H_2/O_2 system, kg/s
G_W	mass flow of feed water injected to H_2/O_2 system, kg/s
H_u	lower heating value (LHV) of fuel, kJ/kg
I_{EP}	comprehensive performance index, $/kWh
N_{gt}	semi-closed gas turbine power, MW
N_{ho}	H_2/O_2 system power, MW
N_{st}	steam turbine power, MW
P	pressure, bar
R_C	ratio of C_P to C_E
R_S	steam injection coefficient, $R_S = G_S/(G_S + G_W)$
T	temperature, °C
T_3	inlet temperature of semi-closed gas turbine
T_4	outlet temperature of semi-closed gas turbine
W_{O_2}	energy consumption for O_2 production, kWh/kg O_2
X_{CO_2}	CO_2 recovery ratio, $X_{CO_2} = (G_{CO_20} - G_{CO_2})/G_{CO_20}$

Greek symbols

α_{O_2}	purity of O_2 at outlet of membrane separator
π	pressure ratio
η_e	IGCC auxiliary power ratio, %
η_{ig}	net IGCC system efficiency, % (LHV)
Φ	ratio of outlet pressure to inlet pressure of membrane separator

Generally, five ways to separate and recover CO_2 from the IGCC system have been summarized and analyzed as follows [1,2]: (1) CO_2 separation and recovery from the exhaust fuel gas; (2) CO_2 sequestration before combustion; (3) CO_2 sequestration by a polygeneration system that combines the IGCC system with chemical processes; (4) CO_2 recovery using integrated thermal cycles with fuel oriented transfer; and (5) CO_2 separation and recovery based on a novel thermal cycle, for example, the semi-closed O_2/CO_2 cycle IGCC system proposed by Paolo [3]. Its combustion products mainly consist of CO_2 and H_2O, and hence, it separates CO_2 without extra energy consumption. However, the O_2 production and CO_2 recovery demand large energy consumptions. The energy penalty for separating and recovering CO_2 will bring an efficiency decrease of about 7 percentage points. The IGCC system with dual cycles (DC-IGCC) and less CO_2 emission is another example [2]. Its efficiency decrease is less than 4 percentage points after separating and recovering CO_2 (as the flow diagram of the DC-IGCC system is shown in Fig. 1).

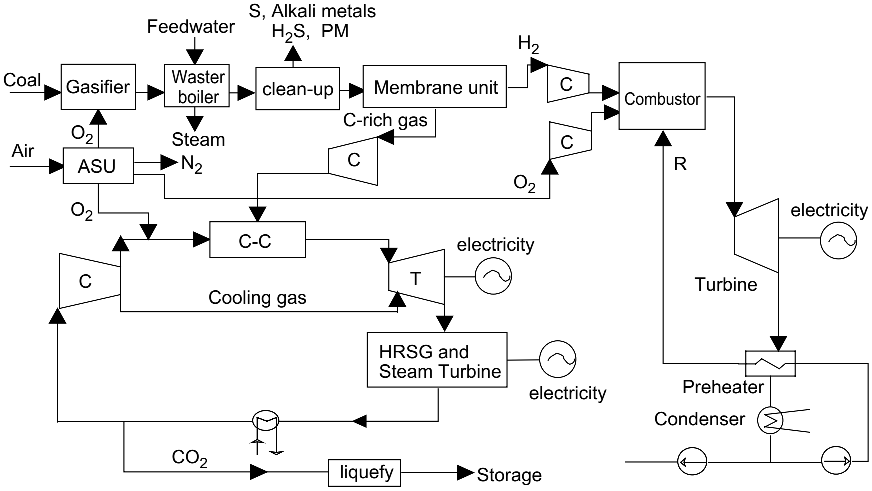

Fig. 1. Flow chart of IGCC system with dual cycles.

Based on the above researches, this paper proposes a novel IGCC system with low CO_2 emission. The paper is to analyze the thermodynamic characteristics, environmental and comprehensive performance of the new system, to study the effect of a new method of O_2 production on the system performance and to compare the system performances of different IGCC systems with O_2/CO_2 cycle.

2. Novel IGCC system with less CO_2 emission

As shown in Fig. 1, the DC-IGCC system employs the advanced ceramics proton membrane technology to separate the clean syngas into H_2 rich gas and C rich gas [11,12]. The C rich gas is fed into the gas turbine combustor using pure oxygen as the oxidizer. The combustion products mainly consist of CO_2 and H_2O. Because the purity of H_2 is very high (99.99%), the H_2 can constitute a H_2/O_2 cycle with pure O_2 from the air separation unit (ASU). Though the DC-IGCC system has a high efficiency after separating and recovering CO_2, there exist a big potential to improve the system performance. Unsaturated feed water with high pressure is fed into the combustor of the H_2/O_2 cycle. Its temperature is about 100 °C. However, the theoretical combustion temperature of H_2 with O_2 is 3000–4000 °C or so. So, there is a big exergy loss of heat transfer in the combustor of the H_2/O_2 cycle. Table 1 shows the exergy loss distributions in the H_2/O_2 cycle, disregarding the exergy loss of the water pump and generator. The largest exergy loss is in the combustor, accounting for 78% of the overall exergy loss of the H_2/O_2 cycle. This indicates that reducing the exergy loss of the combustor is the key to improving this H_2/O_2 cycle. The exergy loss of the combustor chamber includes three parts: (1) the exergy loss caused by H_2 combustion with pure O_2 to the thermal energy at the turbine inlet temperature; (2) the exergy loss caused by water evaporation and the preheating of the reactants of H_2 and O_2; and (3) the exergy loss caused by mixing of the three input streams. The analytical result shows that the exergy loss of the second part is the largest, accounting for 57.5% of the overall exergy loss of the combustor

Table 1
Exergy losses in H_2/O_2 cycle ($R_S = 0.0$)

H_2 compressor	0.755%
O_2 compressor	0.229%
Combustor	78%
Turbine	13.28%
Condenser	5.122%
Preheater	2.614%

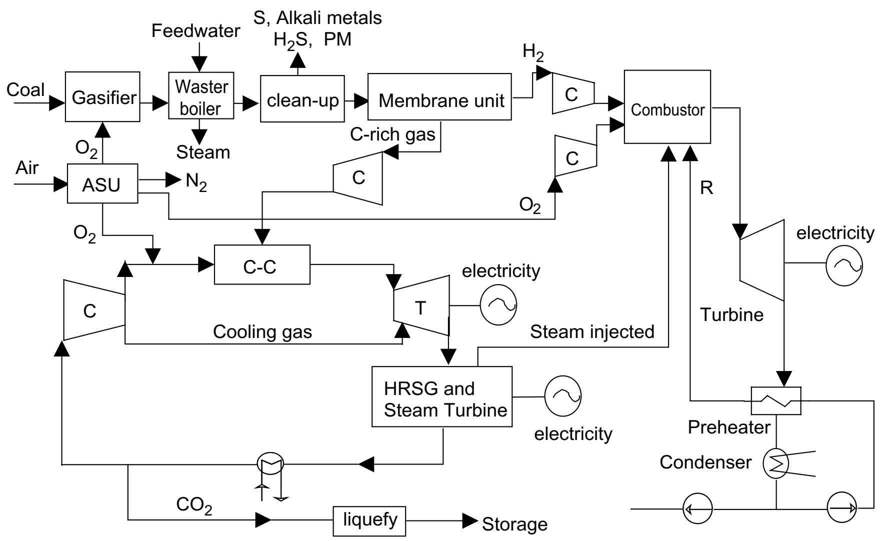

Fig. 2. Flow diagram of IGCC system with steam injected H_2/O_2 cycle and CO_2 recovery.

[5]. Hence, it indicates that reducing the exergy loss caused by heat transfer in the combustor is the key to reducing the overall exergy loss of the combustor.

It should be noted that there is no integration between the two subsystems (H_2/O_2 system, semi-closed Brayton combined cycle) in the DC-IGCC system. However, the synthetic integration of two subsystems will be quite important. If steam, instead of liquid water, is fed into the combustor chamber of the H_2/O_2 cycle, the exergy loss caused by heat transfer will be greatly reduced, and the system efficiency will be improved. Here, the HRSG of the semi-closed Brayton combined cycle may generate the steam for the H_2/O_2 cycle.

Based on the above integration, here, we propose a novel IGCC system with a steam injected H_2/O_2 cycle and CO_2 recovery (as shown in Fig. 2). The flow diagram of the system is similar to that of the DC-IGCC system. The main difference is that the combustor of the H_2/O_2 cycle is not injected by unsaturated feed water but by the superheated steam from the HRSG.

3. Evaluation of novel IGCC system

As a case study, we have taken into account a large scale commercial IGCC power system. It is comprised of a heavy duty gas turbine with high temperature, a steam system with double pressure and reheating system, a steam injected H_2/O_2 cycle (the inlet pressure of the turbine is 20 bar, the inlet temperature of the turbine is 1300 °C), an entrained flow gasifier with oxygen of 98%, a low temperature clean up subsystem, a cryogenic ASU and a ceramic proton membrane separator. The parameters of the steam injected to the H_2/O_2 system are as follows: $P = 22$ bar, $T = 540$ °C. Some evaluation criteria defined in this paper are:

Evaluation criterion for system performance

This paper employs the net IGCC system efficiency (η_{ig}) as the evaluation criterion of system performance.

$$\eta_{ig} = \frac{(N_{gt} + N_{st} + N_{ho}) \times (1 - \eta_e)}{G_{cl} \times H_u} \tag{1}$$

Evaluation criterion for environmental performance

The CO_2 specific emission (G_{CO_2}) is taken as the evaluation criterion of system environmental performance.

$$G_{CO_2} = G_{CO_2 0}(1 - X_{CO_2}) \tag{2}$$

Here $G_{CO_2 0}$ is the CO_2 specific emission from the system without CO_2 recovery and X_{CO_2} is the CO_2 recovery ratio.

3.1. Analytical method of thermal system

Generally, we use two kinds of methods, thermal equilibrium method and exergy method, to analysis the thermal system. The former focuses on the quantity of energy, regardless of the quality of the energy. The latter takes into account both the quantity and quality of the energy. It has the advantage over the former method of disclosing both the positions and magnitudes of energy losses in the thermal system. In this paper, we chiefly employ the thermal equilibrium method to analysis the overall system performance and, simultaneously, use the exergy method to find the potential of improving the system performance.

3.2. Significant role of steam injection on H_2/O_2 system and overall IGCC system

Fig. 3 shows the effect of steam injection coefficient (R_S) on the exergy loss distributions in the H_2/O_2 cycle. The exergy losses of the H_2 compressor and O_2 compressor are quite stable. The exergy losses of the turbine, condenser and preheater are increased with the increase of R_S. The exergy loss of the combustor is decreased quickly. Because the mass flow of steam injected in the H_2/O_2 system (G_S) will be increased with the increase of R_S, the exergy loss caused by heat transfer in the combustor will be decreased. The proportion of the exergy loss of the combustor in the H_2/O_2 cycle will be decreased gradually.

Table 2 shows the exergy loss distributions in the H_2/O_2 cycle when the combustor is entirely injected by steam. Compared with the previous system with water fed into the H_2/O_2 cycle, the proportion of the combustor exergy loss in the H_2/O_2 cycle is decreased from 78.0% to 58.7%. The exergy loss of combustor is reduced by 24.6% and decreased from 116.69 kJ/mol H_2 to 87.97 kJ/mol H_2, which will greatly improve the overall IGCC system performance.

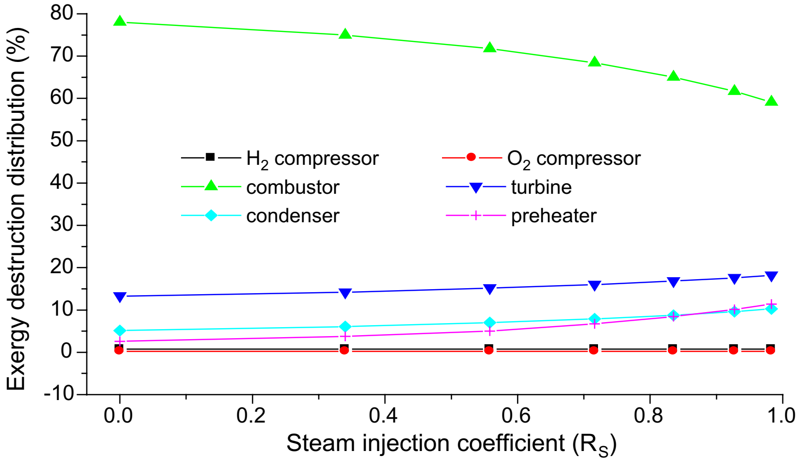

Fig. 3. Effect of steam injection coefficient (R_S) on exergy destruction distributions in H_2/O_2 cycle.

Table 2
Exergy losses in H_2/O_2 cycle ($R_S = 1.0$)

H_2 compressor	0.753%
O_2 compressor	0.229%
Combustor	58.72%
Turbine	18.26%
Condenser	22.038%
Preheater	0%

Fig. 4 shows the variation of power with steam injection coefficient. Because the gas turbine system of the semi-closed Brayton cycle is not influenced by steam injected in the H_2/O_2 system, the semi-closed gas turbine power (N_{gt}) is unchanged. Both the steam turbine power (N_{st}) and H_2/O_2 system power (N_{ho}) are changed with the increase of steam injection coefficient (R_S). N_{st} is decreased due to the decrease of mass flow of the working substance, while N_{ho} is increased with the increase of mass flow of the working substance. The increment of N_{ho} is greater than the decrement of N_{st}, so the net power and efficiency of the system will be increased.

As shown in Fig. 5, the IGCC system efficiency (η_{ig}) is increased with the increase of steam injection coefficient (R_S). Compared with the DC-IGCC system, η_{ig} is increased by 2.6 percentage points when R_S is 0.98. The CO_2 specific emission from the IGCC without CO_2 recovery ($G_{CO_2 0}$) is decreased gradually with the increase of R_S. The environmental performance of the IGCC system will be improved.

3.3. Investigation of new method of O_2 production

Because the IGCC system with O_2/CO_2 cycle uses pure O_2 as fuel oxidizer and the gasification unit also consumes some O_2, the energy consumption of the ASU (air separation unit) doubles

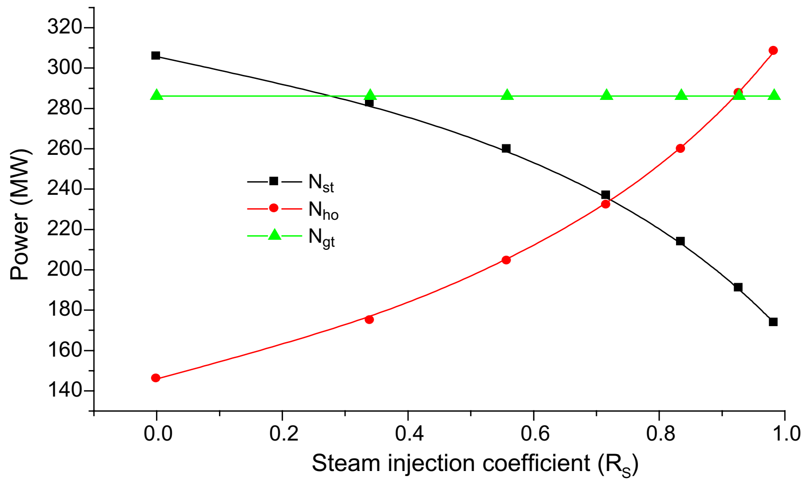

Fig. 4. Variation of power with steam injection coefficient (R_S).

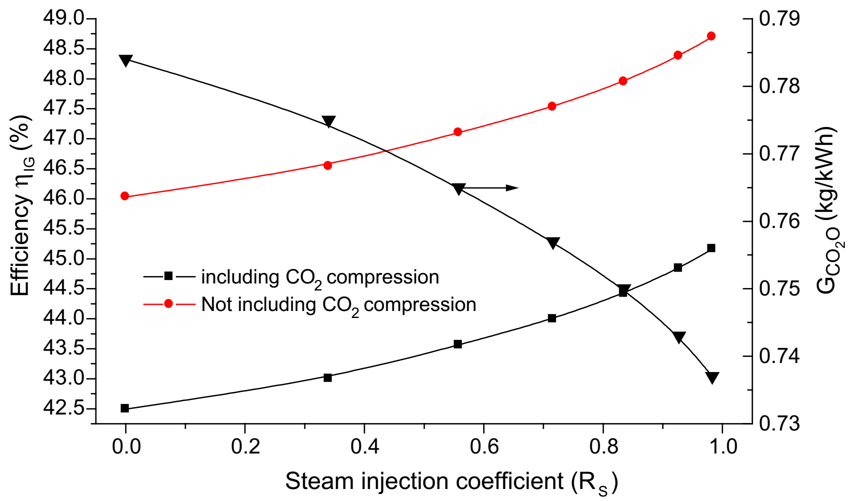

Fig. 5. Variation of efficiency and environmental performance (G_{CO_20}) with steam injection coefficient (R_S).

compared to that of the conventional IGCC system. Oxygen with high purity can be easily acquired by using an ASU with cryogenic separation technology. However, it demands large energy consumption, about 0.269 kWh/kg O_2. An ASU with membrane separation technology has the advantage of lower energy consumption. Until now, the purity of the oxygen is usually lower.

Based on the above two separation methods, Lin [2] has proposed a new ASU using a combined method of membrane separation and cryogenic separation, which combines the advantages of the two separation methods. The flow chart of the new ASU is shown in Fig. 6. Air is firstly separated into oxygen rich air and nitrogen rich air through a membrane separator, and then, the oxygen rich air is separated into N_2 and O_2 through a cryogenic separation unit. The energy

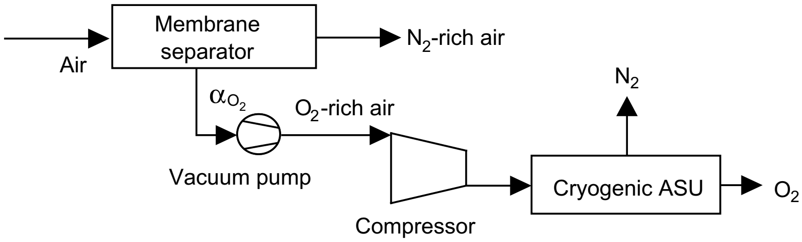

Fig. 6. Flow chart of new air separation unit.

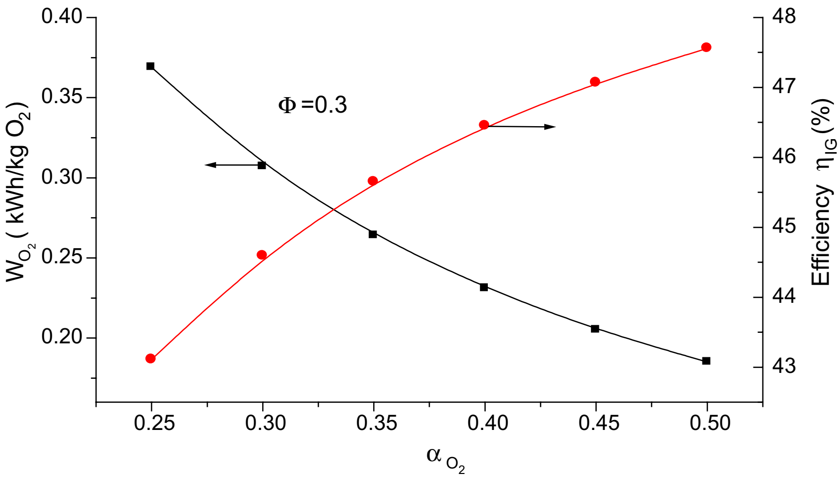

Fig. 7. Variation of IGCC system efficiency (η_{ig}) and energy consumption for O_2 production (W_{O_2}) with purity of oxygen at outlet of membrane separator (α_{O_2}).

consumption of the ASU will be decreased if the IGCC system employs the new ASU. Fig. 7 shows the variation of the energy consumption for O_2 production (W_{O_2}) and η_{ig} with the purity of O_2 at the outlet of the membrane separator (α_{O_2}). With current technology, α_{O_2} can reach 0.4 by using a membrane separation method. When α_{O_2} is 0.4, W_{O_2} may be decreased to 0.231 kWh/kg O_2. η_{ig} may be increased to 46.45%, which is improved by 1.3%.

4. New evaluation approach of IGCC system with CO_2 recovery

As shown in Fig. 8, the higher CO_2 recovery ratio (X_{CO_2}) is, the better the environmental performance of the IGCC system is and the lower the IGCC system efficiency is. That is, improvement of the system environmental performance will give rise to the decline of system thermal efficiency. The reverse is true. So, neither the IGCC system efficiency (η_{ig}) nor the CO_2 specific emission (G_{CO_2}) can be employed to evaluate the system overall performance properly.

In order to evaluate comprehensively the IGCC system performance, we need to employ a new evaluation criterion. The traditional method uses the cost of electricity (COE), including the CO_2

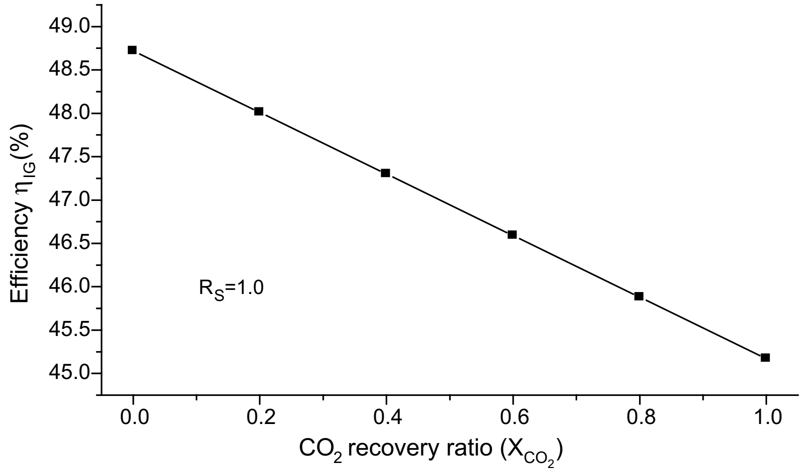

Fig. 8. Variation of IGCC system efficiency with CO_2 recovery ratio (X_{CO_2}).

emission cost, as the evaluation criterion. Here, we propose a comprehensive performance index (I_{EP}) of energy consumption and environmental pollution. I_{EP} is related to both the fuel cost and CO_2 emission cost, taking no account of the cost of investment. The index uses the international currency (for example, dollar) to quantify the thermal efficiency and environmental performance of the IGCC system. It is defined as follows:

$$I_{EP} = C_E b + C_P G_{CO_2} \tag{3}$$

Here C_E is fuel price; C_P is CO_2 penalty price; b is fuel consumption ratio; G_{CO_2} is CO_2 specific emission; R_C is the ratio of C_P to C_E and $b = 3600/(\eta_{ig}H_u)$, $C_P = R_C C_E$, then

$$I_{EP} = C_E[3600/(\eta_{ig}H_u) + R_C G_{CO_2 0}(1 - X_{CO_2})] = f(R_C, \eta_{ig}, X_{CO_2}) \tag{4}$$

From Eq. (4), we can know this new criterion is a multi-objective function, concerning the system efficiency, environmental effect and economic factor. In this paper, I_{EP} is used as the optimization objective function to evaluation the comprehensive performance.

4.1. Comprehensive performance of IGCC system

Fig. 9 shows the comprehensive performance index (I_{EP}) versus CO_2 recovery ratio (X_{CO_2}) with different R_C. When R_C is less than 0.05, it has a small effect on I_{EP}. I_{EP} is changed slightly with the change of X_{CO_2}. When R_C is greater than 0.1, it has a large effect on I_{EP}. As shown in Fig. 9, I_{EP} is decreased with the increase of X_{CO_2}. Namely, the higher X_{CO_2} is, the better the comprehensive performance of the IGCC system is. Accordingly, R_C is an important factor that influences the IGCC system comprehensive performance.

Fig. 10 shows the comprehensive performance index (I_{EP}) versus CO_2 recovery ratio (X_{CO_2}) with different fuel prices (C_E). It is clear that I_{EP} increases with the increase of C_E, and the comprehensive performance of IGCC system becomes lower and lower (I_{EP} increases).

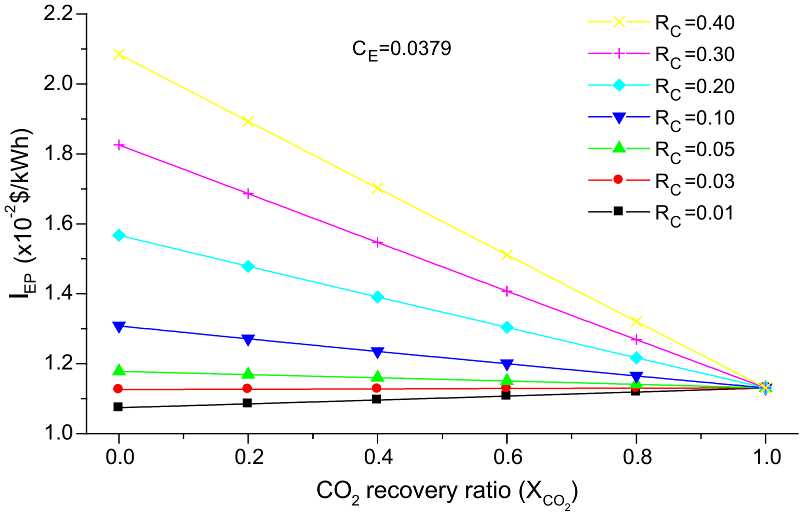

Fig. 9. Variation of comprehensive performance index (I_{EP}) with CO_2 recovery ratio (X_{CO_2}) and different R_C.

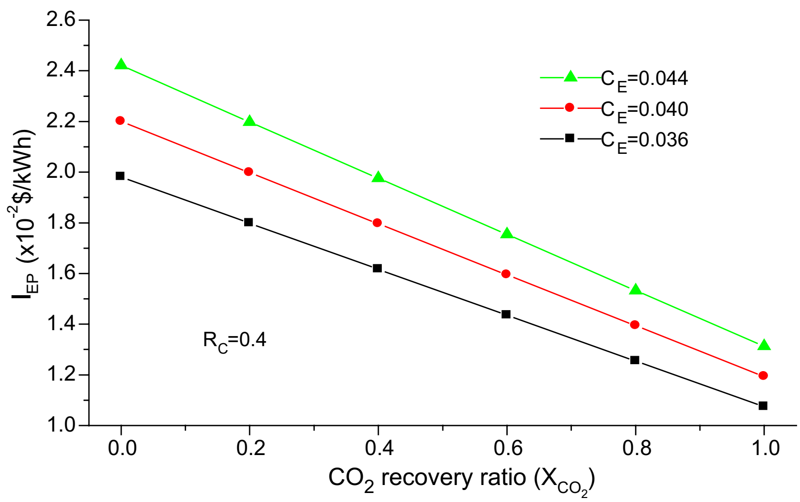

Fig. 10. Variation of comprehensive performance index (I_{EP}) with CO_2 recovery ratio (X_{CO_2}) and different fuel prices (C_E).

4.2. Comprehensive performance comparisons of different IGCC systems with O_2/CO_2 cycle

IGCC systems with O_2/CO_2 cycle can be classified into two kinds of systems according to the criterion whether the syngas is separated into C rich gas and H rich gas before combustion.

For the simple semi-closed O_2/CO_2 cycle without syngas separation, clean syngas is directly fed into the combustion chamber using pure O_2 as the oxidizer. Compared with the base IGCC system without CO_2 recovery, the simple semi-closed O_2/CO_2 cycle IGCC system has a big efficiency decrease of about 7% [3].

For the O_2/CO_2 cycle with syngas separation, clean syngas is firstly separated into C rich gas and H rich gas by using the membrane separator, and then, they are fed into the gas turbine systems, respectively. For instance, Hendriks [4] has proposed a dual gas turbine cycle IGCC system. The flow chart is shown in Fig. 11. C rich gas is fueled with pure O_2. Because of the low purity of H_2, the hydrogen is fed to a conventional gas turbine and fueled with air. After separating and recovering the CO_2, its efficiency decrease is about 6% and less than that of the IGCC with simple semi-closed O_2/CO_2 cycle. If the purity of H_2 can attain 99.99% by using the advanced membrane separation technology, H_2 can be fed into the H_2/O_2 system, which will result in improvement of the overall system performance. For example, the efficiency decrease of the DC-IGCC system is less than 4% [2]. Accordingly, the performance of the IGCC with O_2/CO_2 cycle and syngas separation is better than that with the simple semi-closed O_2/CO_2 cycle.

Table 3 shows an overall performance comparison between the different IGCC systems with CO_2 recovery when C_P is 0.016 \$/kg and R_C is 0.422. As shown in Table 3, compared with the DC-IGCC system, the new IGCC system efficiency is increased by 2.7 percentage points. Compared with the base IGCC system without CO_2 recovery, the system efficiency is decreased by less than 1 percentage point. Therefore, the new IGCC system has the smallest efficiency decrease after recovering the CO_2. At the same time, the comprehensive performance index of the new IGCC system is the smallest, so its comprehensive performance is the highest.

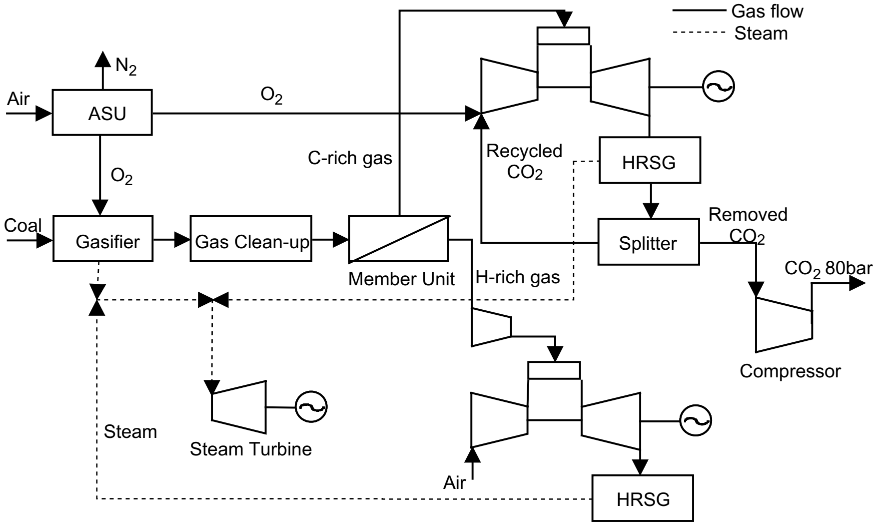

Fig. 11. Flow diagram of dual gas turbine cycle IGCC system with CO_2 recovery.

Table 3
Performance comparisons between different IGCC systems

	Base IGCC system	DC- IGCC system	IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery
π	18	23	23
T_3 (°C)	1288	1288	1288
T_4 (°C)	588	725	725
R_S	–	0.0	1.0
R_C	0.422	0.422	0.422
C_E ($/kg)	0.0379	0.0379	0.0379
N_{gt} (MW)	279.5	286.14	286.14
N_{st} (MW)	184.15	305.68	169.0
N_{ho} (MW)	–	145.93	312.95
b (kg/kWh)	0.293	0.317	0.298
X_{CO_2}	0.0	1.0	1.0
η_{ig} (%)	46.0	42.493	45.18
G_{CO_2} (kg/kWh)	0.86	0.0	0.0
I_{EP} ($/kWh)	0.0248	0.012	0.0113

5. Conclusion

A new IGCC system with semi-closed Brayton cycle and steam injected H_2/O_2 cycle has been proposed to recover CO_2 effectively. The research results show the overall IGCC system performance is greatly improved by injecting steam, instead of water, into the combustor of the H_2/O_2 cycle. The new system only has an efficiency decrease of less than 1% for separating and recovering the CO_2. A new evaluation criterion for system comprehensive performance I_{EP} can synthetically evaluate the overall IGCC system performance. The ratio of CO_2 penalty price to fuel price (R_C) is the key factor affecting the system comprehensive performance. The comparative results of different IGCC systems with O_2/CO_2 cycle show that the performance of the IGCC with O_2/CO_2 cycle and syngas separation is better than that with the simple semi-closed O_2/CO_2 cycle. In addition, reducing the energy consumption for O_2 production will be helpful to improve the overall performance of the IGCC system with O_2/CO_2 cycle.

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