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.

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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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Generally, five ways to separate and recover CO₂ from the IGCC system have been summarized and analyzed as follows [1,2]: (1) CO₂ separation and recovery from the exhaust fuel gas; (2) CO₂ sequestration before combustion; (3) CO₂ sequestration by a polygeneration system that combines the IGCC system with chemical processes; (4) CO₂ recovery using integrated thermal cycles with fuel oriented transfer; and (5) CO₂ separation and recovery based on a novel thermal cycle, for example, the semi-closed O₂/CO₂ cycle IGCC system proposed by Paolo [3]. Its combustion products mainly consist of CO₂ and H₂O, and hence, it separates CO₂ without extra energy consumption. However, the O₂ production and CO₂ recovery demand large energy consumptions. The energy penalty for separating and recovering CO₂ will bring an efficiency decrease of about 7 percentage points. The IGCC system with dual cycles (DC-IGCC) and less CO₂ emission is another example [2]. Its efficiency decrease is less than 4 percentage points after separating and recovering CO₂ (as the flow diagram of the DC-IGCC system is shown in Fig. 1).
Based on the above researches, this paper proposes a novel IGCC system with low CO₂ 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 O₂ production on the system performance and to compare the system performances of different IGCC systems with O₂/CO₂ cycle.

2. Novel IGCC system with less CO₂ emission

As shown in Fig. 1, the DC-IGCC system employs the advanced ceramics proton membrane technology to separate the clean syngas into H₂ 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 CO₂ and H₂O. Because the purity of H₂ is very high (99.99%), the H₂ can constitute a H₂/O₂ cycle with pure O₂ from the air separation unit (ASU). Though the DC-IGCC system has a high efficiency after separating and recovering CO₂, there exist a big potential to improve the system performance. Unsaturated feed water with high pressure is fed into the combustor of the H₂/O₂ cycle. Its temperature is about 100 °C. However, the theoretical combustion temperature of H₂ with O₂ is 3000–4000 °C or so. So, there is a big exergy loss of heat transfer in the combustor of the H₂/O₂ cycle. Table 1 shows the exergy loss distributions in the H₂/O₂ 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 H₂/O₂ cycle. This indicates that reducing the exergy loss of the combustor is the key to improving this H₂/O₂ cycle. The exergy loss of the combustor chamber includes three parts: (1) the exergy loss caused by H₂ combustion with pure O₂ to the thermal energy at the turbine inlet temperature; (2) the exergy loss caused by water evaporation and the preheating of the reactants of H₂ and O₂; 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.
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\textsubscript{2}/O\textsubscript{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\textsubscript{2}/O\textsubscript{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\textsubscript{2}/O\textsubscript{2} cycle.

Based on the above integration, here, we propose a novel IGCC system with a steam injected H\textsubscript{2}/O\textsubscript{2} cycle and CO\textsubscript{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\textsubscript{2}/O\textsubscript{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

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**Table 1**

<table>
<thead>
<tr>
<th>Process</th>
<th>Exergy Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H\textsubscript{2} compressor</td>
<td>0.755%</td>
</tr>
<tr>
<td>O\textsubscript{2} compressor</td>
<td>0.229%</td>
</tr>
<tr>
<td>Combustor</td>
<td>78%</td>
</tr>
<tr>
<td>Turbine</td>
<td>13.28%</td>
</tr>
<tr>
<td>Condenser</td>
<td>5.122%</td>
</tr>
<tr>
<td>Preheater</td>
<td>2.614%</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Flow diagram of IGCC system with steam injected H\textsubscript{2}/O\textsubscript{2} cycle and CO\textsubscript{2} recovery.
pressure and reheating system, a steam injected H2/O2 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 H2/O2 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 (\(\eta_{ig}\)) as the evaluation criterion of system performance.

\[
\eta_{ig} = \frac{(N_{gt} + N_{st} + N_{ho}) \times (1 - \eta_c)}{G_{cl} \times H_u}
\]

Evaluation criterion for environmental performance
The CO2 specific emission (\(G_{CO2}\)) is taken as the evaluation criterion of system environmental performance.

\[
G_{CO2} = G_{CO20} (1 - X_{CO2})
\]

Here \(G_{CO20}\) is the CO2 specific emission from the system without CO2 recovery and \(X_{CO2}\) is the CO2 recovery ratio.

3.1. Analytical method of thermal system

Generally, we use two kinds of methods, thermal equilibrium method and exergy method, to analyse 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 analyse 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 H2/O2 system and overall IGCC system

Fig. 3 shows the effect of steam injection coefficient (\(R_S\)) on the exergy loss distributions in the H2/O2 cycle. The exergy losses of the H2 compressor and O2 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 H2/O2 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 H2/O2 cycle will be decreased gradually.

Table 2 shows the exergy loss distributions in the H2/O2 cycle when the combustor is entirely injected by steam. Compared with the previous system with water fed into the H2/O2 cycle, the proportion of the combustor exergy loss in the H2/O2 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 H2 to 87.97 kJ/mol H2, which will greatly improve the overall IGCC system performance.
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 H₂/O₂ system, the semi-closed gas turbine power ($N_{gt}$) is unchanged. Both the steam turbine power ($N_{st}$) and H₂/O₂ 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 ($\eta_{ig}$) is increased with the increase of steam injection coefficient ($R_S$). Compared with the DC-IGCC system, $\eta_{ig}$ is increased by 2.6 percentage points when $R_S$ is 0.98. The CO₂ specific emission from the IGCC without CO₂ recovery ($G_{CO2,0}$) 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 O₂ production

Because the IGCC system with O₂/CO₂ cycle uses pure O₂ as fuel oxidizer and the gasification unit also consumes some O₂, the energy consumption of the ASU (air separation unit) doubles

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Table 2
Exergy losses in H₂/O₂ cycle ($R_S = 1.0$)

<table>
<thead>
<tr>
<th></th>
<th>Exergy loss (%)</th>
</tr>
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<tbody>
<tr>
<td>H₂ compressor</td>
<td>0.753%</td>
</tr>
<tr>
<td>O₂ compressor</td>
<td>0.229%</td>
</tr>
<tr>
<td>Combustor</td>
<td>58.72%</td>
</tr>
<tr>
<td>Turbine</td>
<td>18.26%</td>
</tr>
<tr>
<td>Condenser</td>
<td>22.038%</td>
</tr>
<tr>
<td>Preheater</td>
<td>0%</td>
</tr>
</tbody>
</table>

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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 O₂. 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 N₂ and O₂ through a cryogenic separation unit. The energy
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 \( \text{O}_2 \) production (\( W_{\text{O}_2} \)) and \( \eta_{\text{ig}} \) with the purity of \( \text{O}_2 \) at the outlet of the membrane separator (\( \alpha_{\text{O}_2} \)). With current technology, \( \alpha_{\text{O}_2} \) can reach 0.4 by using a membrane separation method. When \( \alpha_{\text{O}_2} \) is 0.4, \( W_{\text{O}_2} \) may be decreased to 0.231 kWh/kg \( \text{O}_2 \). \( \eta_{\text{ig}} \) may be increased to 46.45%, which is improved by 1.3%.

4. New evaluation approach of IGCC system with \( \text{CO}_2 \) recovery

As shown in Fig. 8, the higher \( \text{CO}_2 \) recovery ratio (\( X_{\text{CO}_2} \)) 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 (\( \eta_{\text{ig}} \)) nor the \( \text{CO}_2 \) specific emission (\( G_{\text{CO}_2} \)) 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 \( \text{CO}_2 \)
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:

$$I_{EP} = C_E b + C_P G_{CO2}$$

Here $C_E$ is fuel price; $C_P$ is CO$_2$ penalty price; $b$ is fuel consumption ratio; $G_{CO2}$ 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

$$I_{EP} = C_E [3600/(\eta_{ig} H_u) + R_C G_{CO2;0}(1 - X_{CO2})] = f(R_C, \eta_{ig}, X_{CO2})$$

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 evaluate the comprehensive performance.

### 4.1. Comprehensive performance of IGCC system

Fig. 9 shows the comprehensive performance index ($I_{EP}$) versus CO$_2$ recovery ratio ($X_{CO2}$) 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 $X_{CO2}$. 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 $X_{CO2}$. Namely, the higher $X_{CO2}$ 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 ($X_{CO2}$) 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).
4.2. Comprehensive performance comparisons of different IGCC systems with O₂/CO₂ cycle

IGCC systems with O₂/CO₂ 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.

Fig. 9. Variation of comprehensive performance index ($I_{EP}$) with CO₂ recovery ratio ($X_{CO₂}$) and different $R_C$.

Fig. 10. Variation of comprehensive performance index ($I_{EP}$) with CO₂ recovery ratio ($X_{CO₂}$) and different fuel prices ($C_E$).
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.
5. Conclusion

A new IGCC system with semi-closed Brayton cycle and steam injected H₂/O₂ cycle has been proposed to recover CO₂ effectively. The research results show the overall IGCC system performance is greatly improved by injecting steam, instead of water, into the combustor of the H₂/O₂ cycle. The new system only has an efficiency decrease of less than 1% for separating and recovering the CO₂. A new evaluation criterion for system comprehensive performance $I_{EP}$ can synthetically evaluate the overall IGCC system performance. The ratio of CO₂ penalty price to fuel price ($R_C$) is the key factor affecting the system comprehensive performance. The comparative results of different IGCC systems with O₂/CO₂ cycle show that the performance of the IGCC with O₂/CO₂ cycle and syngas separation is better than that with the simple semi-closed O₂/CO₂ cycle. In addition, reducing the energy consumption for O₂ production will be helpful to improve the overall performance of the IGCC system with O₂/CO₂ cycle.

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References


