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The Novel Design of an IGCC System with Zero Carbon Emissions

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The integrated gasification combined cycle (IGCC) is a clean power generation system which consists of the coal gasification process, combined heat and power (CHP) processes and carbon capture processes. The IGCC consumes less water than traditional pulverized coal plants since it uses the gas turbines. The coal gasification process produces the syngas as the fuel of the gas turbine which not only improves the power efficiency but also the pollutants under combustion are reduced. To improve the carbon capture efficiency, the oxy-fuel combustion is a very efficient option but the conventional cryogenic air separation unit (CASU) consumes a lot of energy such that the total power efficiency is dramatically decreased. A new design of chemical looping air separation (CLAS) is presented. The simulation shows that the proposed CLAS with low energy consumption and high purity oxygen can replace the CASU.

1. Introduction

The integrated gasification combined cycle (IGCC) power generation technology is one of the most efficient clean coal power generation technologies (Wang et al., 2016). By virtue of the coal gasification and gas purification technology, the IGCC power generation technology has the advantages of high efficiency, cleanness, water saving, wide adaptability to fuel, easy realization of multi generation (Kanniche et al., 2010). At present, the coal-fired power generation technology with carbon dioxide capture technologies including the pre-combustion capture, the post combustion capture, the oxygen enriched combustion capture. The oxygen enriched combustion capture process is simple by using a return flue gas instead of nitrogen oxygen as diluent. The oxygen enriched combustion capture is considered to be a very effective way to capture. The enriched oxygen combustion technology has two sources, one is the traditional cryogenic air separation technology (CASU), another is a high temperature chemical loop air separation technology (CLAS) (Kong et al., 2012). However, the low temperature air separation technology consumes a large amount of electricity, the oxygen rich combustion consumes the gross output of the power plant 8 - 9 %. The conventional thermal power plant net output efficiency is about 37.5 %, but the oxygen enriched combustion is added to reduce the efficiency about 28 %.

Notably, it not only loss a lot of revenue of the power plant, but also it increases the cost of investment. On the other hand, the chemical loop air separation technology may overcome the shortcomings where the CLAS can save the power consumption about 10 % of the traditional ASU and it can enhance the concentration of carbon dioxide of exhausted gases. (Shah et al., 2014). However, the CLAS should face a number of technical problems, such as oxygen carrying experience caused by sintering deactivation, oxidation at high temperature and so on.

Many studies have shown that the doping of the carrier and a certain proportion of inert monomer (such as silica, spinel) can effectively increase the mechanical strength of the oxygen carrier to prevent the oxygen carrier sintering.

Shah points out that the reason for the reduction of the oxygen carrying state at high temperature is that it is possible to carry out the oxidation reaction with the special oxygen partial pressure higher than the ambient pressure. Cai et al. (2010) studied on the cobalt based oxygen carrier of oxygen and the pressure effect in the

oxidation reaction. Wang et al. (2016) shows that the Cu based oxygen carrier significantly decreases the oxygen consumption of the oxygen releasing reaction.
This paper uses Aspen plus to model the IGCC system coupling with oxygen enriched combustion capture. The overall efficiency analysis of the power system and the capture effect were successfully addressed.

2. Oxygen carrier characteristics

The studies of oxygen carriers have shown that Mn_2O_3 begins to decompose at 700 °C (Mei et al., 2013). The equilibrium pressure of oxygen can reach 0.11 bar at 750 °C, and oxygen equilibrium pressure is 0.16 bar at 800 °C. The equilibrium pressure at 850 °C is the same as it at 800 °C, but the rate of decompose at 850 °C is twice that of 800 °C (Wang et al., 2016). Oxygen absorption of the oxygen carrier is satisfied that the oxygen partial pressure in the air is not less than the oxygen equilibrium partial pressure of the oxygen carrier at this temperature.
According to Dalton's law of partial pressure, the increasing the pressure of the air can increase the oxygen partial pressure. The oxygenation reaction can be carried out at a high temperature by raising the air pressure. Figure 1 shows the relationship of the amount of air required for the conversion of 40 moles of manganese tetroxide to manganese dioxide at 850 °C for oxygenation. As can be seen from the figure, the air flow decreases as the pressure increases, and when the pressure is higher than 5 bar, the air flow changes a little.

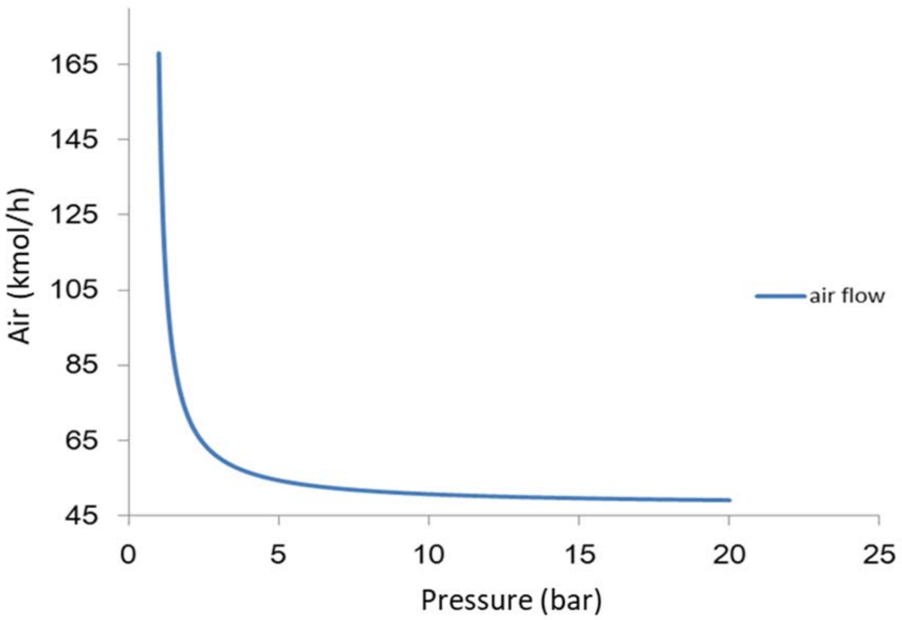

Figure1: Air required vs pressure for the conversion of oxygen to manganese dioxide at 850 °C

3. Process design

Figure 2 is a flow chart of the IGCC using the oxygen-enriched combustion coupled with the CASU process. Fresh air is separated into nitrogen and oxygen by air separation system. The oxygen flow I split to two parts, one is sent to the gasifier for coal gasification and another is mixed with the return fuel gas (RFG) and fed into the combustor of gas turbine. The syngas out of the gasification reactor is passed through the waste heat boiler to recover the waste heat, removing the ash, desulfurizing, and removing the impurities, then flows into the gas turbine combustion chamber. After the gas turbine, the waste heat is used to produce the electricity through the Rankine cycle.
Figure 3 is a flow chart of the IGCC using the oxygen-enriched combustion coupled with the conventional CLAS. The fresh air is passed into the oxidation reactor to react with the reduced oxygenated manganese trioxide to produce manganese oxide. The manganese dioxide is sent to a reduction reactor to carry out an oxygen release reaction.

The heat released from the oxide reactor is used to produce high pressure steam. The heat required for the reduction of the oxygen carrier is supplied by methane combustion. Reducing the equilibrium partial pressure of oxygen in the reactor by introducing water vapor.
The oxygen released from the oxygen evolution is withdrawn from the water vapor. After the heat exchange, the condensed oxygen is separated from the water to obtain pure oxygen for IGCC oxygen-enriched combustion.

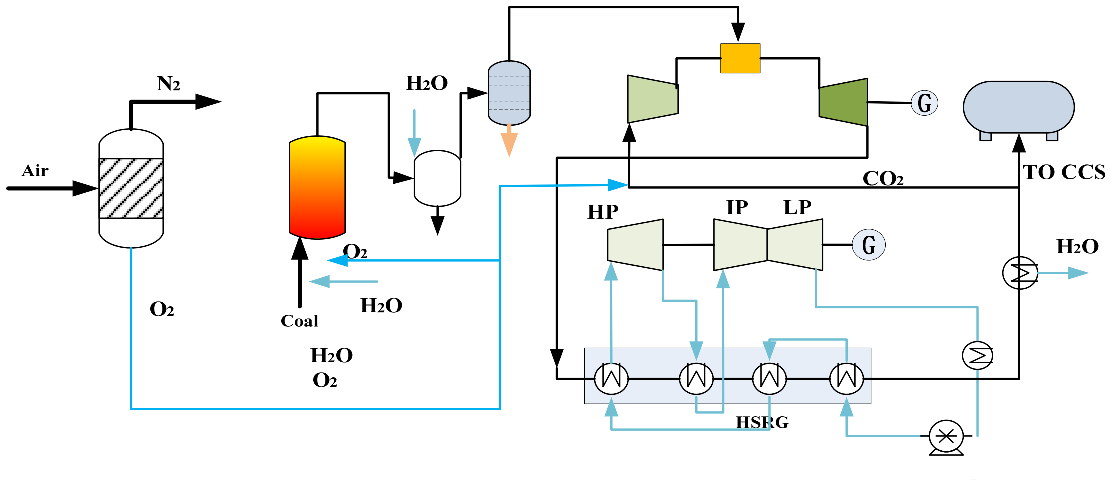

Figure 2: IGCC using the oxygen-enriched combustion coupled with the CASU process

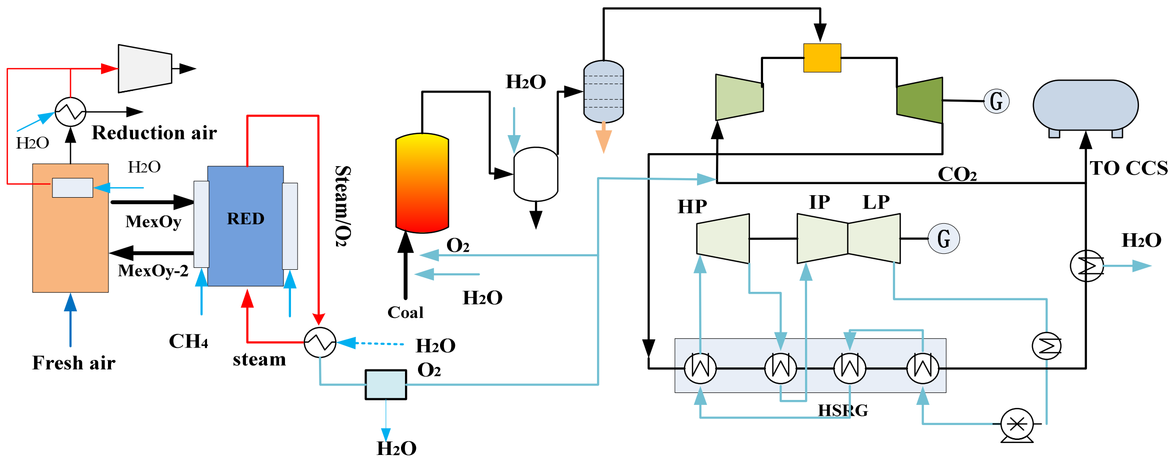

Figure 3: IGCC using the oxygen-enriched combustion coupled with the conventional CLAS

Figure 4 is a flow chart of the IGCC using the oxygen-enriched combustion coupled with the batch-type CLAS. From the first part of the manganese-based oxygen carrier performance analysis shows that in the high-pressure environment, oxygen in the oxidation reactor and fresh air can be higher than the reduction temperature under the conditions of oxidation reaction.
After the oxygen is oxidized completely, the high-pressure water vapor is passed, and the remaining air in the reactor is drained, and then the pressure is reduced. When the pressure of the oxidation reactor is reduced to the ambient pressure, the atmospheric water vapor is passed. The temperature is higher than the reduction temperature, the Gibbs free energy minimization principle can be obtained by the oxygen carrier reduction reaction will occur automatically. Since the fresh air passing into the reactor will take away the heat from the partial oxidation reaction, some of the methane combustion is required to ensure that the oxygen carrier can be completely reduced.
The high temperature and high-pressure air coming out of the oxidation reactor is reduced the pressure by external expansion work and discharged with fresh high-pressure air after heat exchange. The difference

between the oxygen oxidation of the pressurized oxidative chemical circuit and the conventional chemical circuit is that the oxidation and reduction of its oxygen carrier is carried out in a reactor. The oxidation and reduction of the oxygen carrier are controlled by changing the composition of the passing gas. In the pressurized oxidative oxygenation circuit, the inert carrier plays an important role in increasing the mechanical strength and transferring heat of the oxygen carrier. From the above analysis, it can be seen that the oxygen carrier needs a higher oxygen partial pressure at high temperature to maintain the conversion rate, however the reduction reaction needs to run under normal pressure as shown in Figure 4, In order to achieve continuous oxygen production to meet the needs of oxy-fuel combustion system, Oxygen was alternately produced using two identical reactors.
The specific process is: the fresh air is pressurized by the compressor and then heat exchanged with the air having a low oxygen content discharged from the gas turbine. Finally, the fresh air after the heat exchange is passed to the reactor to react with the reduced oxygen carrier.

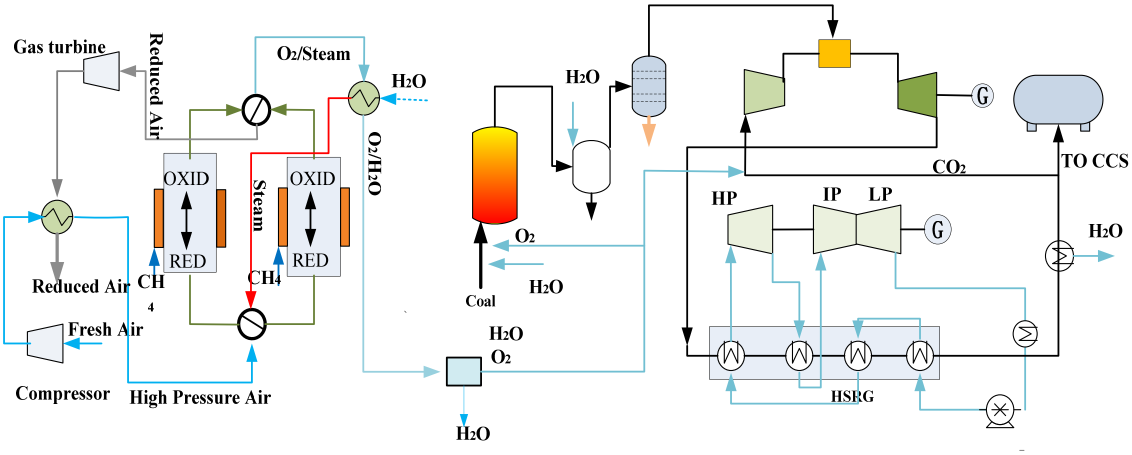

Figure 4: IGCC using the oxygen-enriched combustion coupled with the batch-type CLAS

The heat released by the process is used to raise the oxygen carrier itself and the inert carrier.
The high temperature and high-pressure oxygen discharged from the reactor is externally operated by the gas turbine and discharged with fresh high-pressure air after heat exchange.
Until the oxygen in the reactor is completely oxidized and then reduced to atmospheric pressure to reduce the deoxidation reaction. The released oxygen is condensed by the heat exchanger and separated from the water to obtain the pure oxygen for the oxygen-enriched combustion process.

4. Results and discussion

Table 1 shows the elemental analysis of coal and its high calorific value. The simulation selection criteria is shown in Table 2.

Table 1: Elemental analysis and industrial analysis of coal

Ash	Carbon	Hydrogen	Nitrogen	Chlorine	Sulfur	Oxygen	Heat
7.59	78.03	5.06	1.69	0	1.97	5.66	29.71 MJ/kg

Table 2: Specifications and operating conditions

Parameters	Unit	Design 1	Design 2	Design 3
Gasifier temperature	°C	1,200	1,200	1,200
Gasifier pressure	bar	30.3	30.3	30.3
Gas turbine inlet temperature	°C	1,400	1,400	1,400
Gas turbine exhaust temperature	°C	650	650	650
OXID rector temperature	°C	-	800	850
RED rector temperature	°C	-	800	800
OXID rector pressure	bar	-	1.01	1.01
RED rector pressure	bar	-	1.01	1.01

Table 3 is the composition of the compressed gas. The CO_2 content of the working conditions 2 and 3 was the highest, the volume fraction could reach 99 %.
Case 1 (oxygen content with 95 % oxygen content) was only 94.24 %. From the above data the IGCC using the oxygen-enriched combustion system is more superior to the air-separation system. It is owing that the CLAS reduce the energy demand for separating nitrogen and oxygen of air.

Table 3: Compressed flue gas composition

	Vol (O_2) %	Vol (N_2) %	Vol (H2O) %	Vol (CO_2) %	Vol (NO) %	Vol (NO_2) %	Vol (SO_2) %	Vol (SO_3) %	Vol (AR) %
Design 1	0.32	1.67	0.05	94.24	2.10E-05	0	0.0034	1.10E-05	3.72
Design 2	0.34	0.58	0.07	99	1.30E-05	0	0.0036	1.20E-05	0
Design 3	0.34	0.58	0.07	99	1.30E-05	0	0.0036	1.20E-05	0

$$\eta = \frac{W_{net}}{CH_4(HHV) + coal(HHV)} \quad (1)$$

Equation 1 is the net efficiency calculation formula. W_{net} is the net power of output, *CH_4(HHV),* and *coal(HHV)* is the heat of methane and coal respectively. Table 4 is the overall efficiency of the three designs. It can be seen that the oxygen oxidation efficiency of the pressurized chemical looping is significantly better than that of the conventional chemical looping. The oxygen production efficiency of Design 3 is 35 kgO_2 / $kgCH_4$, and the oxygen production efficiency of Design 2 is 7.47 kgO_2 /$kgCH_4$. By Design 2, the CLAS process power generation is 222.5 MW. By Design 3, the CLAS process power generation is 34.7 MW. In Design 2, the heat released by the oxidation reactor cannot be transferred to the reduction reactor for the recovery of power generation, and the heat released from the oxygen evolution in Design 3 is accumulated by the carrier itself and the inert carrier. In the reduction, the amount of external heating required for the reduction of oxygen is significantly reduced. The net efficiency of the system by Eq. (1) is 35.5 %.
In Design 2, the net efficiency of the oxygen-enriched combustion system using conventional chemical circuit oxygen is 40.2 %. By Design 3, the net efficiency of 40.7 %. This indicates that the oxygen-rich combustion system using the pressurized oxidative chemical circuits is superior to other designs.

Table 4: Overall efficiency

Parameters	Unit	Design 1	Design 2	Design 3
Methane flow requirement	kg/s	-	12.7	1.926
Coal consumption	kg/s	23.14	23.14	23.14
Stream turbine	MW	149	149	149
Gas turbine	MW	167	167	167
Power of CLAS	MW		222.5	34.7
Boiler feed pump	MW	2.83	2.83	2.83
Desulfurization power	MW	3.16	3.16	3.16
Miscellaneous	MW	3	7.1	3.51
ASU kWh/t O_2		250	-	-
Oxygen requirement	kg/s	50.56	101.4	58.3
Oxygen plant power	MW	36.7	-	-
CPU kWh/t CO_2		135	135	135
CO_2 for CPU plant	kg/s	60	94.9	67.4
CPU power demand	MW	26.35	41.67	29.6
Gross power production	MW	316	538.5	350.7
Net power	MW	244.41	483.74	311.6
Net efficiency	%	35.5	40.2	40.7

5. Conclusions

In this article, the modeling and energy efficiency of the IGCC system coupling with CLAS is successfully addressed. The mains merits include:

1. It is verified that the energy efficiency of the proposed IGCC power system is higher than the conventional IGCC system using CASU.
2. The CLAS uses the high-pressure oxidation reactor to increase the heat transfer amount between two reactors. It is shown that the high pressure for the oxidation reactor can increase the yield of oxygen up to 35 $kgO_2/kgCH_4$.
3. The net efficiency of the IGCC coupled with the batch-type CLAS by Eq. (1) can achieve about 40.7 %.

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