An Advanced Cryogenic Air Separation Process for Integrated Gasification Combined Cycle (IGCC) Systems

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An advanced cryogenic air separation unit (ASU) process for integrated gasification combined cycle (IGCC) system is proposed based on self-heat recuperation technology. In the proposed ASU process, only one distillation column was used in contrast to double columns in the conventional ASU process. The N_2 product gas from the top of the distillation column is first compressed, and then exchange heat with the air liquid from the bottom using the self-heat recuperation technology. Thus, both the latent heat and the sensible heat of the N_2 product steam are circulated, resulting in a significant reduction of energy consumption in cryogenic ASU process. In addition, the exergy destruction of the compressors, which contributes to the largest part in previous study, is significantly reduced as no high-pressure column is used in the proposed process. The simulation results show that the total energy consumption of the proposed cryogenic air separation process is reduced by around 30 % compared with the conventional cryogenic air separation process for IGCC systems.

1. Introduction

Integrated gasification combined cycle (IGCC) system is a promising technology for power generation in fossil fuel based power plant (Kanniche et al., 2010). Compared with the widely used pulverized coal combustion power plants, IGCC systems possess higher efficiency, greater fuel flexibility, and are easier for CO_2 capture. A typical IGCC system consists of an air separation unit (ASU), a gasification unit, a water-gas shift unit, a CO_2 separation unit and a gas turbine combined cycle unit (Figure 1). In this process, high purity O_2 (95 %) is firstly produced in the ASU, and then sent to the gasification unit, in which the pure oxygen reacts with coal and other feedstocks to produce raw syngas. The raw syngas, which is mainly composed of CO and H_2, is further converted to CO_2 and H_2 in a water-shift unit. After the water-shift unit, CO_2 is separated from the syngas in the CO_2 separation unit and ready for storage, while H_2 is used for combustion in a combined cycle containing a gas turbine, a heat recovery steam generator and a steam turbine (Frey and Zhu, 2006).

To date, IGCC system is not widespread commercialized due to its high operating cost. Air separation unit is one important unit that significantly affects the efficiency and operating cost of IGCC systems. Air separation can be achieved by various technologies, such as cryogenic distillation, adsorption and membrane separation technologies (Smith and Klosek, 2001). Although the latter two processes have become more competitive, cryogenic distillation process is still the first choice for large amount of O_2 production in high purity (Smith and Klosek, 2001). Thus, it is also suggested to be used in IGCC systems due to the large amount of O_2 requirement. The conventional cryogenic air separation unit usually contains one high-pressure column, one low-pressure column and one main heat exchanger. To reduce the energy consumption, the condenser of high-pressure column is usually combined with the reboiler of low-pressure column. By exchanging the latent heat of N_2 condensation in high-pressure column and O_2 vaporization in low-pressure column, the energy consumption of conventional cryogenic air separation unit can be reduced. However, to make sure that heat can be transferred from the condenser to the reboiler, a large pressure difference is required between the high- and low-pressure columns to maintain a minimum

temperature difference. As a consequence, a large amount of energy is consumed to maintain the pressure difference between the high- and low-pressure columns, largely reducing the energy consumption of IGCC systems.

To lower the operating cost and improve the efficiency, one alternative approach is to integrate cryogenic ASU with IGCC by injecting N_2 produced in cryogenic ASU to gas turbine and extracting air from compressors of gas turbine for input to cryogenic ASU. Frey and Zhu estimated alternative types of ASU and gas turbine integration involving N_2 injection, air extraction and combinations of both under different ASU pressures (Frey and Zhu, 2006). They recommended that the optimal N_2 injection only combined with an elevated pressure ASU had the highest efficiency, power output and the lowest emissions. Another approach is to design novel cryogenic air separation processes that consume less energy. In this case, using exergy analysis to localize, quantify and further reduce the thermodynamic losses in cryogenic ASU has been widely conducted. Cornelissen and Hirs (1998) have conducted an exergy analysis on a air separation plant including an argon separation column, and reported that the exergy losses are mainly caused by the liquefaction unit. Van der Ham and Kjelstrup (2010).conducted the exergy analysis of two cryogenic ASU processes integrated with IGCC using N_2 injection, which have two and three columns The authors concluded that the ASU process with three-column design destroyed 12 % less exergy than the two-column design. Fu et al (2012) conducted the exergy analysis of a cryogenic ASU process for oxy-combustion, and pointed out that the energy consumption of ASU cannot be significantly reduced unless the flowsheet structures are improved

Recently, a self-heat recuperation technology had been developed and applied in the distillation process, significantly reducing the energy consumption Kansha et al. (2009) and later Kansha et al. (2011). The objective of this study is to propose an advanced cryogenic ASU process based on self-heat recuperation technology for IGCC systems. The N_2 gas from the top of the distillation column is compressed, and exchanged heat with the liquid in the bottom and feed streams, eliminating the condenser and reboiler. Both the conventional and proposed processes are simulated for comparison.
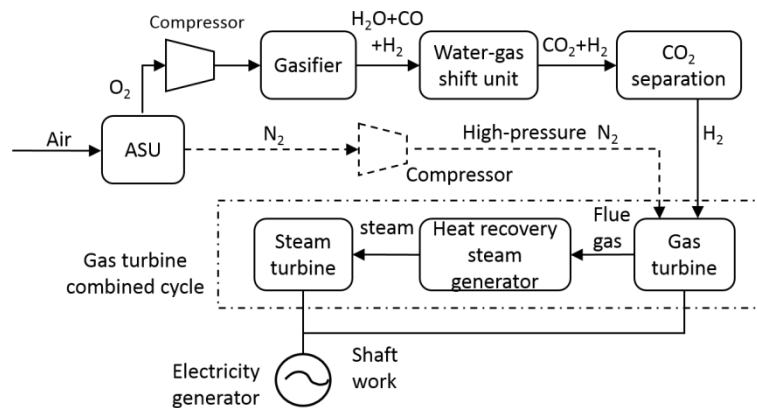

Figure 1: A schematic flow chart of gasification combined cycle (IGCC) with pre-combustion CO_2 capture

2. Process description and calculation

2.1 Conventional cryogenic air separation process

Figure 2 shows the flowsheet of a typical conventional double-column cryogenic air separation process for IGCC system. In this process, ambient air is firstly compressed to 550 kPa in the main air compressor, and cooled to room temperature (S1-1→S1-2→S1-3). Then the ambient air is split into two streams (S1-4, S1-5). The first stream (S1-4) is cooled to near dew point in the main heat exchanger (HXM) before feeding into the high-pressure column (550 kPa, 30 stages). The second stream (S1-5) was cooled to around −140°C, and then depressurized and feed into the low-pressure column (150 kPa, 30 stages). In the high-pressure column, liquid N_2 and O_2-rich air liquid are separated by distillation. The liquid N_2 (S3-1) from the top of the high-pressure column is subcooled, throttled and fed into the top of low-pressure column as liquid reflux (S3-1→S3-2→S3-3). The O_2-rich air liquid from the bottom of the high-pressure column is subcooled, depressurized and fed into the middle of low-pressure column as feed (S2-1→S2-2→S2-3). After distillation in low-pressure column, high purity O_2 (S6-1) is obtained at the bottom, while high purity N_2 (S4-1) and low purity N_2 (S5-1) are obtained at the top of low-pressure column. Then these products flow through the subcooler and main heat exchanger as coolant (high-purity N_2: S4-1→S4-2→S4-3→S4-

Figure 2: Process configuration of conventional cryogenic air separation process

4→S4-5; low-purity N_2: S5-1→S5-2→S5-3→S5-4). As the cryogenic ASU is used for IGCC system, the high purity N_2 and O_2 are pressurized to 8,800 kPa and 4,800 kPa to meet the requirement of gasification unit and gas turbine.

2.2 Proposed cryogenic air separation process

Figure 3 shows a novel cryogenic air separation process based on self-heat recuperation technology for IGCC. The ambient air is compressed, cooled to near dew point in the main heat exchanger (S1-1→S1-2→S1-3→S1-4), and then feed into the distillation column, in which the air is separated into O_2 (S2-1), low purity (LP) N_2 (S3-1), and high purity (HP) N_2 (S4-1). The high purity N_2 is split into two streams: reflux stream (S4-2) and product HP N_2 (S4-8). The reflux stream S4-2 is compressed to exchange heat with the O_2 reflux stream in heat exchanger (HX1), and then cooled to near boiling point in heat exchanger HX2 and HX4 (S4-2→S4-3→S4-4→S4-5→S4-6→S4-7). The O_2 stream (S2-1) is also split into two streams: reflux stream (S2-2) and product stream (S2-7). The stream S2-2 is throttled and exchanged heat in heat exchanger HX1, and then adjusted to near dew point by exchanging heat in heat exchanger HX4 before flowing back to distillation column (S2-2→S2-3→S2-4→S2-5→S2-6). Accordingly, the stream of O_2 product, HN N_2, and LP N_2 product are depressurized and act coolant in heat exchangers HX2, HX3 and HX4. The key point of this distillation module is to maintain that the boiling point of N_2 is higher than that of O_2 in HX1 by adjusting the pressure of these two streams. As a consequence, neither condenser nor reboiler is required in this process, which significantly reduced the energy consumption. To meet the requirement of gas turbine and gasification unit, the products N_2 and O_2 gas are compressed to 8,800 and 4,800 kPa after the distillation module.

Figure 3: Process configuration of proposed cryogenic ASU based on self-heat recuperation technology

Table 1: Conditions and specification of the conventional and proposed processes

Name	Conventional process	Proposed process
Temperature of feed air	298.15 K	298.15 K
Pressure of feed air	101 kPa	101 kPa
Pressure of HP column	550 kPa	--
Pressure of LP column	150 kPa	--
Pressure of DC in proposed process	--	300 kPa
O_2 mole fraction	99.99 %	99.99 %
High-purity N_2 mole fraction	99 %	99 %
ΔT_{min} in Main heat exchanger	1.5 K	1.5 K
ΔT_{min} in Main condenser between HP column and low column	1 K	--
ΔT_{min} in HX1	--	1.2 K
ΔT_{min} in HX2	--	6 K
ΔT_{min} in HX3	--	10 K
ΔT_{min} in HX4	--	24K

2.3 Process simulation

Both the two flow sheets were simulated with a process simulator PRO II 9.1, using Peng-Robinson equation as the state. We assumed that the composition of feed air was 80 mol% N_2 and 20 mol %O_2 at standard temperature (298.15 K) and pressure (101 kPa). The stage number for high-pressure column, low-pressure column and distillation column were 10, 20 and 50. The adiabatic efficiency in all compressors was assumed to be 100 %, and the pressure drop in all columns was assumed to be 0. The flow rate of feed air was assumed as 14,650 kmol h^{-1} at standard temperature (298.15 K) and pressure (101 kPa). The other detailed conditions and specification of the conventional and proposed process are shown in Table 1.

3. Results and Discussion

3.1 Energy consumption
Table 2 shows the detailed properties of product streams of these two processes. The mole fractions of the product streams in these two processes are almost same, and all meet the specification. Table 3 shows the energy consumption for the two processes. As no additional energy input is required, the energy input is only due to the input work of compressors and output work of expanders. The work of booster compressors (9,825 kW) after ASU was not accounted into the total energy consumption of ASU, as their aim is to increase the pressure of product O_2 and N_2 to meet the requirement of the gasification unit and gas turbine.
For the conventional ASU process, the energy input of the conventional process was only due to the work of the compressors (25,232 kW) before the main heat exchanger. Accordingly, the specific energy consumption for the conventional process was 33.12 kJ/mol-O_2. In contrast, the total energy input of the proposed process was only 14,743 kW, which was composed of the work of compressors (14,814 kW) before the main heat exchanger, the work of compressors (1,978 kW=1,107 kW+871 kW) in the distillation section and the output work (−2,049) of expanders. Accordingly, the specific energy consumption for the proposed process was only 19.5 kJ/mol-O_2. Compared to the energy consumption of conventional ASU process, the energy consumption of the proposed process was reduced by around 41.6 %. Even when the expanders were not accounted, the energy consumption was also reduced by 33.4 %.

Table 2: Properties of product streams of the conventional and proposed processes

	Conventional process			**Proposed process**		
	O_2	High-purity N_2	Low-purity N_2	O_2	High-purity N_2	Low-purity N_2
Amount (Nm^3/h)	61,437	108,950	157,772	61,443	108,954	157,751
Pressure (kPa)	110	110	110	110	110	110
Temperature (ºC)	−37.5	−37.5	−37.5	23.5	23.5	23.5
X_{N2}	0.05	0.995	0.9572	0.05	0.995	0.9575
X_{O2}	0.95	0.05	0.0425	0.95	0.05	0.0425

Table 3: Energy consumption of the conventional and proposed processes

Name	Work input/output in conventional process	Work input/output in proposed process
Compressors for pre-processing	25,232 kW	14,814 kW
Compressors in distillation section	--	1,978 kW
Expanders	--	–2,049 kW
Total energy input	25,232 kW	14,743 kW
Specific energy input	33.12 kJ/mol-O_2	19.34 kJ/mole O_2

3.2 Energy and material flow

To compare the detailed heat duty and energy flow in these two processes, the energy and material flow diagrams of these two ASU processes are shown in Figure 4. The boxes represent units, solid lines represent the flow of materials, and dash lines represent the flow of energy/work. For better understanding, a heat exchanger was divided into a heat transmitter (HT) and a heat receiver (HR).

Comparing these two processes, it can be seen that the main reason for the energy saving in the proposed process is due to the good internal heat circulation in the distillation module (circulated by dot line). In the distillation module of the proposed process, heat (10,415 kW) from the top product N_2 was transferred to product O_2 at the bottom based on self-heat recuperation technology, and circulated in the distillation process. Thus, neither reboiler nor condenser was required in the distillation module of the proposed process, significantly reducing the energy consumption. Figure 5 shows the temperature-heat duty diagram of the proposed process based on self-heat recuperation technology. It can be found that the heat paring matched quite well, which largely reduced the exergy losses. Notably, an amount of waste heat, which was almost same to the input of the compressor (CP) before the pre-cooling unit, was removed in the pre-cooling unit in both processes. This amount of heat can be used to pre-heat the N_2 and O_2 to meet the high temperature in gas turbine or gasification unit, which will further reduce the total energy consumption of IGCC unit.
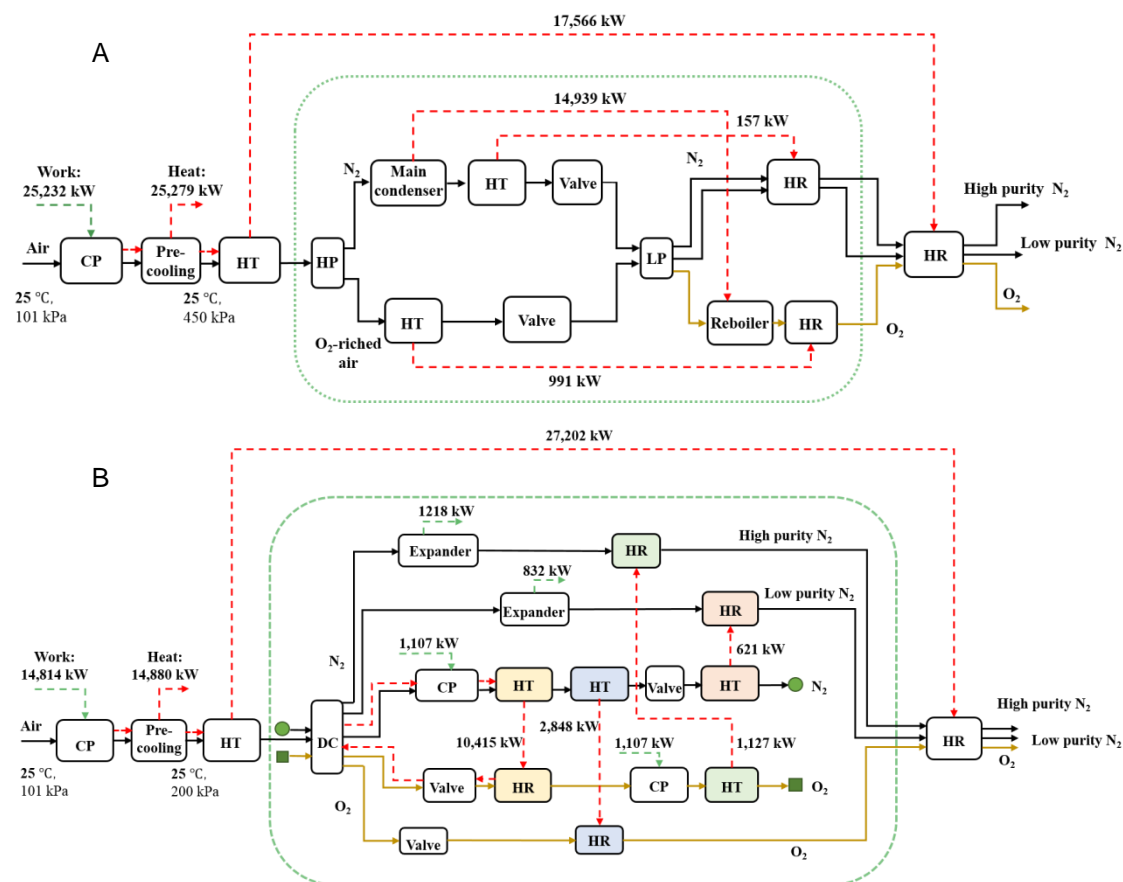

Figure 4: Energy and materials flow diagrams of conventional cryogenic ASU process (A) and proposed process based on self-heat recuperation technology (B)
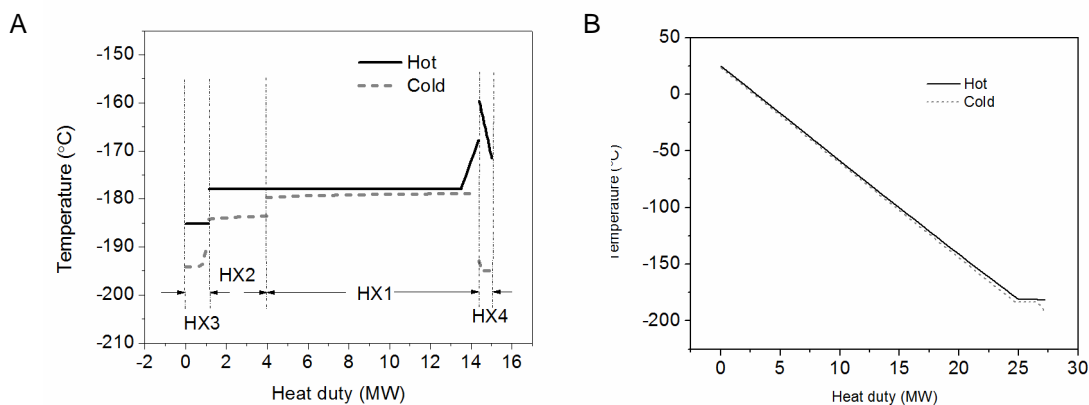
Figure 5 Temperature-heat duty diagrams of heat exchangers in distillation module (A) and the main heat exchanger (B) in the proposed process based on self-heat recuperation technology

4. Conclusion

An advanced cryogenic ASU based on self-heat recuperation technology for IGCC system is proposed in this study. Only one distillation column was used in contrast to double columns in the conventional ASU. The N_2 product gas from the top of the distillation column is compressed, and exchange heat with the air liquid in the bottom and feed streams using the self-heat recuperation technology. Thus, both the latent heat and the sensible heat of the process steam are circulated, resulting in a large reduction of energy consumption in ASU. In addition, the exergy destruction of the compressors (which contributes to the largest part in previous study) is significantly reduced as no high-pressure column is used in the proposed process. The simulation results show that the energy consumption of the proposed cryogenic air separation process is decreased by around 30 % compared with the conventional cryogenic air separation process for IGCC systems.

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