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Techno-economic evaluation of an elevated temperature pressure swing adsorption process in a 540 MW IGCC power plant with CO_2 capture

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Abstract

Pressure swing adsorption at elevated temperature (ET−PSA) is one kind of widely studied acid gas clean up technology. In this study, a system scheme for a 540 MW IGCC system with CO_2 capture is proposed by integrating the current developing ET−PSA process. The modeling framework is developed and implemented in process simulation platform (Aspen Plus) by considering 90% of CO_2 removal rate and 99% of H_2S removal rate. The system performance is simulated for comparing the effects with adopting Selexol process on the system efficiency and integration characteristics. The simulation is based on the same coal feed rate, gas turbine combustion temperature and stack gas temperature. The simulated results show that with the H_2 recovery rate increases from 75% to 100%, the net plant efficiency for IGCC with ET−PSA process increases linearly from 23.1% to 34.4%, and when the H_2 recovery rate exceeds 93.5%, the estimated efficiency can be higher than that for IGCC with Selexol process (31.5%).

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Keywords: CO_2 capture, elevated temperature PSA; Techno-economic evaluation

1. Introduction

It is widely recognized that global warming is mainly caused by anthropogenic CO_2 emissions. Among all the sources, coal fired power plants make the biggest contribution to CO_2 emissions. Integrated gasification combined cycle with CO_2 capture and sequestration (IGCC+CCS) is one of the promising clean coal technologies which can

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achieve high CO_2 recovery by taking the advantages of high partial pressure (1.0~2.0 MPa) of CO_2 in the syngas after water gas shift reaction. The commercially available technologies for CO_2 capture for IGCC, such as Selexol, MEA, Rectisol, etc, commonly cool the syngas stream down to low temperature which leads to large amount of sensitive heat loss. Previous studies show the significance of CO_2 separation process at elevated temperature and predict the promising direction in efficiency improvement by application of warm gas clean up.

Elevated temperature pressure swing adsorption (ET−PSA) is one kind of current developing warm gas clean up technologies. It has been widely studied in the aspects of adsorbent development [1,2,3], model optimization [4], and pilot plant test [5]. In previous study, our group has successfully developed a high performance adsorbent used in ET−PSA process from interlayer potassium-promoted stearate-pillared hydrotalcite precursors [6]. On this basis, a system level model for elevated temperature PSA process was developed in the gPROMS commercial simulation platform by considering comprehensive coupling effects from mass, heat, and momentum transport mechanisms [7,8]. It fully realized the flexible configuration and modular design for the different cases of PSA system.

In this study, two system schemes for IGCC system with CO_2 capture are proposed by integrating the current developing elevated temperature pressure swing adsorption process and Selexol process respectively. The system models, which mainly include air separation unit, coal gasifie, water gas shift section, acid gas removal section, CO_2 compression section, gas turbine and steam turbine, are based on the Cost and Baseline Performance study by NETL on 2007 and 2010 [9,10]. The system performance is simulated for comparing the effects of adopting elevated temperature PSA process and Selexol process on the system efficiency and integration characteristics. The simulation is based on the same coal feed, gas turbine combustion temperature and stack gas temperature. To simplify analysis, PSA subsystem is taken as a black box in the Aspen Plus model and the detailed operation process in it is neglected. CO_2 and H_2S removal rate in PSA process are artificially set as 90% and 99% respectively. H_2 recovery rate, which is the main standard of energy consumption in ET−PSA, is considered between 75% and 100%. The simulated results show that with the H_2 recovery rate increases from 75% to 100%, the net plant efficiency for IGCC with ET−PSA process increases linearly from 23.1% to 34.4%, and when the H_2 recovery rate exceeds 93.5%, the estimated efficiency can be high than that for IGCC with Selexol process (31.5%).

2. Modeling

According to many years' operating experience of IGCC power plant, the U.S. Department of Energy (DOE) proposed several sets of IGCC models in 2007 and 2010 [9,10]. In this study, the IGCC model with Selexol process is built based on the arrangement form and operating data coming from case 2 in reference [10]. Some appropriate simplifications are used compared with case 2 to facilitate the analysis. Then, the PSA subsystem is added in the original model to replace the Selexol unit. A program written by Fortran language is embedded in the IGCC model to forecast the mole flow and component proportion of outlet steams in PSA subsystem.

2.1. IGCC system model with Selexol process

An overall flowsheet schematic of IGCC model with Selexol process is show in Fig. 1.

The system model includes eight subsystems: Texaco gasifier subsystem (TEXACO), air separation subsystem (ASU), water gas shift subsystem (SHIFT), cooling subsystem (COOL), acid gas removal subsystem (SELEXOL), CO_2 compression subsystem (CO2-COMP), gas turbine subsystem (GT) and steam turbine subsystem (ST). The model is built based on the total generating capacity of 540 MWe. The plant utilizes Texaco gasifier to process 5302 tonnes/day of Illinois NO.6 coal. Proximate and elemental analysis of coal is shown in Table 1 [11].

Table 1. Proximate and elemental analysis of Illinois NO.6 coal.

Proximate analysis/ % (by mass)				Ultimate analysis (dry)/ % (by mass)						HHV/ MJ/kg
Moisture	Ash (dry)	Volatile matter (dry)	Fixed carbon (dry)	Ash	C	H	N	O	S	
11.12	9.70	34.99	44.19	9.70	63.75	4.50	1.25	6.88	2.51	27.11

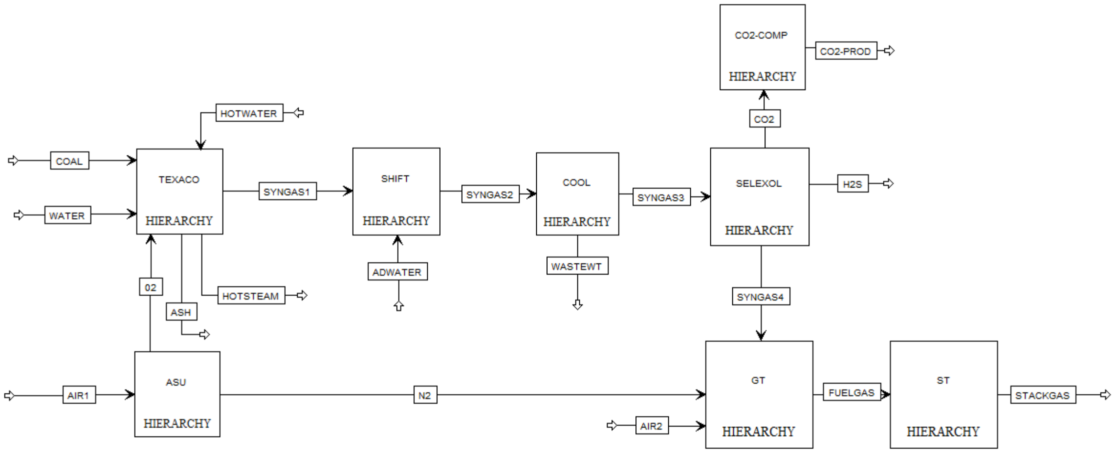

Fig. 1. Schematic of IGCC flowsheet with Selexol process

Coal and a given amount of water are mixed to prepare a concentration of 63% slurry. Then it is fed to Texaco-GE gasifier after pressurizing to 5.79 MPa with the oxygen coming from ASU (95% pure) after four-stage intercooling compressing. Oxygen flow is controlled to ensure that the gasified pressure and temperature are kept in 5.6 MPa, 1316 ^{o}C. After gasification, syngas is cooled to 677 ^{o}C by radiant heat exchange, and the heat generated is used to produce 13.8 MPa of saturated steam. Syngas is further cooled to about 200 ^{o}C through quench and water scrubbing before exiting gasifier subsystem. It then enters the two-stage water gas shift system, and the H_2O/CO mole ratio is adjusted to 2 by adding high pressure steam. CO is converted to CO_2 in the gas shift reactors, and the CO conversion rate is 80% per stage.

To achieve the required working temperature of acid gas removal unit, syngas is cooled in the three-stage cooling system from 226 ^{o}C to 35 ^{o}C. A two-stage Selexol process is adopted to remove H_2S and CO_2 successively in the syngas. The removed H_2S (30.7% pure) is reduced to elemental sulfur in the Claus unit (not shown in system); the removed CO_2 (95.0% pure) is compressed to 15.27 MPa in a four-stage intercooling compressor.

The purified gas then enters gas turbine subsystem, and is heated back to 240 ^{o}C with the heat from by-product steam generated by cooling system. The gas expands from 5.1 MPa to 3.173 MPa before entering combustor. Air is divided into two flows after entering GT subsystem. One is compressed to 3.2 MPa and is mixed with purified gas and nitrogen from ASU to burn in the combustor. Air flow is controlled to keep the burning temperature stay at about 1400 ^{o}C. The fuel gas expands in the gas turbine to do work, with the pressure decreasing from 30 bar to 1.064 bar and the temperature decreasing to 609.4 ^{o}C. The exhaust gas from gas turbine is mixed with the other flow of air to lower its temperature to 590.7 ^{o}C. It then enters steam turbine system and is cooled to 137.7 ^{o}C in a two-stage heat recovery boiler (HRSG) before being discharged. In the meanwhile, a certain amount of 13.8 MPa, 534 ^{o}C steam is generated, which subsequently flows through team turbines (HP 3.45 MPa, IP 0.44 MPa, LP 0.1 MPa) to do work. The steam is cooled to 38.4 ^{o}C in the condenser and compressed to 13.8 MPa in the pump to implement a circulation.

2.2. IGCC system model with ET−PSA process

An overall flowsheet schematic of IGCC model with Selexol process is show in Fig. 2.

The main difference between the IGCC systems with ET−PSA process (shown in Fig. 2) and Selexol process (shown in Fig. 1) is the absence of cooling subsystem, that is, the shifted gas with temperature of 226 ^{o}C is directly fed into PSA subsystem without being cooled. Because of this, the main part of steam is carried by shifted gas into PSA subsystem, in turn carried into gas turbine subsystem. The remaining steam which enters CO_2 compression subsystem is condensed and separated. The purified gas then enters gas turbine subsystem without being reheated to 240 ^{o}C, which is another difference between the two systems discussed.

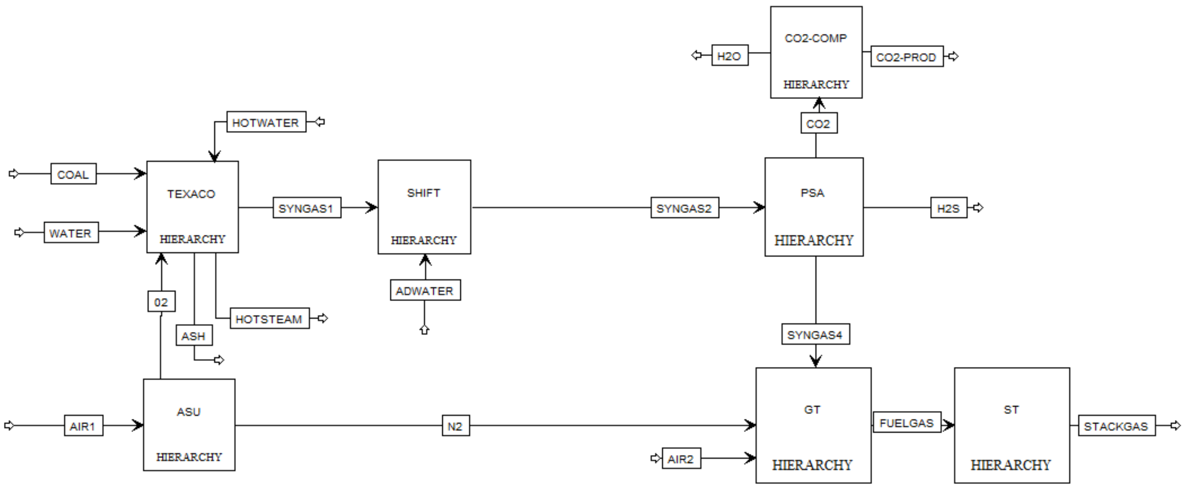

Fig. 2. Schematic of IGCC flowsheet with ET−PSA process

As is mentioned before, PSA subsystem in this Aspen Plus model is considered as a black box with 90% of CO_2 removal rate and 99% of H_2S removal rate. The desorption pressure (P_{regen}) is defined as 1 atm. The amount of H_2 lost into the CO_2 stream is the main factor to determine the energy consumption of PSA process [4], so it is considered as a variable in the range of 75% to 100%. The calculated results of purified gas are listed in Table 2.

Table 2. Calculated results of purified gas for IGCC with ET−PSA process

	Shifted gas	Purified gas with H_2 recovery rate of /%					
Mole Frac		75	80	85	90	95	100
H_2O	0.222	0.299	0.300	0.301	0.302	0.303	0.303
H_2S	0.004	0.000	0.000	0.000	0.000	0.000	0.000
H_2	0.435	0.587	0.589	0.590	0.592	0.593	0.595
CO	0.009	0.013	0.013	0.013	0.013	0.013	0.013
CO_2	0.293	0.053	0.050	0.047	0.044	0.042	0.040
Total Flow kmol/hr	38404	21365	22714	24064	25413	26762	28111

It is worth noting that the gasifier, ASU and the water gas shift reactor don't differ from the IGCC system with Selexol process. To make a convenient comparison, gas turbine combustion temperature is kept at 1439 $\pm$ 1 ^{o}C by controlling the amount of air into the gas turbine combustor. In the same way, stack gas temperature is kept at 137 $\pm$ 1 ^{o}C by controlling the amount of circulating water in steam turbine subsystem.

3. Result and discussion

3.1. Comparison with DOE results

Table 3 shows the comparison result of main streams between IGCC with Selexol process we built and DOE model. It can be seen that the simulated result of key parameters, including the total flow, temperature, pressure and proportion of components, fits well with the DOE results within the error rang allowed. Note that the total flow of stack gas is 18.8% smaller than DOE results, which may due to a higher combustion temperature of GT subsystem (smaller amount of air into the combustor for cooling).

Table 4 shows the calculation and verification results of total thermodynamic property of IGCC system model. In the IGCC model we built, steam turbine subsystem is simplified by only considering high pressure water circulation, which leads to a relatively large error in the aspect of power generated by gas turbine. In addition, compressors used in ASU and CO_2 compression subsystems are all four-stage intercooling compressors, which may be different with actual process, thus increasing the total power consumers. For net power and net plant efficiency, however, the error of this model is lower than 5%, which indicating that the IGCC model with Selexol process has predictive capability.

Table 3. Comparison of main streams between IGCC with Selexol process we built and DOE model

	Raw syngas		Shifted gas		Purified gas		Stack gas	
Mole Frac	Model	DOE Report	Model	DOE Report	Model	DOE Report	Model	DOE Report
H_2O	0.1851	0.1369	0.2607	0.2325	0.0000	0.0001	0.1421	0.1222
N_2	0.0155	0.0070	0.0095	0.0044	0.0140	0.0105	0.7598	0.7541
H_2S	0.0073	0.0073	0.0045	0.0047	0.0000	0.0000	0.0000	0.0000
H_2	0.2955	0.3406	0.4215	0.4366	0.8947	0.9139	0.0000	0.0000
CO	0.4097	0.3576	0.0100	0.0060	0.0132	0.0124	0.0000	0.0000
CO_2	0.0869	0.1380	0.2938	0.3082	0.0780	0.0502	0.0145	0.0083
Total Flow kmol/hr	23394	23122	38228	36478	18006	17423	113337	139657
Total Flow kg/hr	465861	465243	733081	705570	108025	90179	3077901	3834352
Temperature °C	1316	1316	236	240	33	35	137	132
Pressure bar	56.0	56.0	54.1	54.1	51.0	51.0	1.0	1.1

Table 4. Calculation and verification results of total thermodynamic property of IGCC system model

thermodynamic property (unit)	DOE Report	Model	Error (%)
gas turbine (MW_e)	464	539	16.3
sweet gas expander (MW_e)	7	7	6.86
steam turbine (MW_e)	264	189	-28.2
total power generation (MW_e)	734	736	2.06
ASU air compressor (MW_e)	67	63	-5.84
oxygen compressor (MW_e)	11	16	55.0
nitrogen compressor (MW_e)	36	52	47.0
CO_2 compressor (MW_e)	31	42	35.6
total power consumers (MW_e)	191	211	10.4
net power (MW_e)	543	525	-3.36
net plant efficiency (% HHV)	32.6	31.5	-3.37

3.2. Thermodynamic property of IGCC system with ET−PSA process

The main energy consumption of the Selexol process contains two aspects: the amount of sensible heat lost when the shifted gas was cooled to 35 °C before entering Selexol subsystem, and the amount of heat needed for the regeneration steps. In the ET−PSA process, the overall thermal efficiency depends on the amount of H_2 lost into the CO_2 stream for rinse step [4]. Fig. 3 shows a comparison of power generation and consumers between IGCC systems with Selexol process and ET−PSA process.

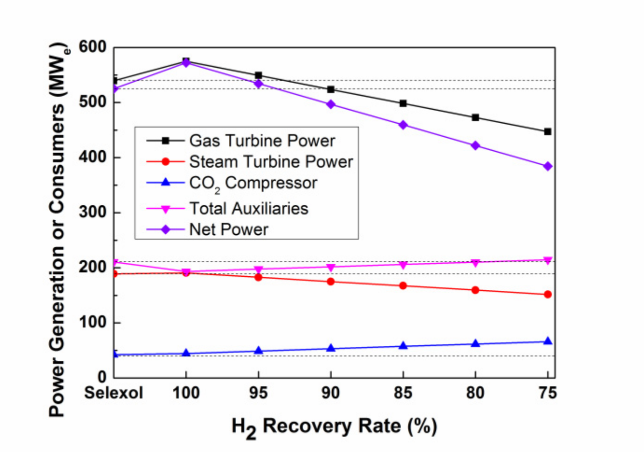

Fig. 3. Comparison of power generation and consumers between IGCC systems with Selexol process and ET-PSA process

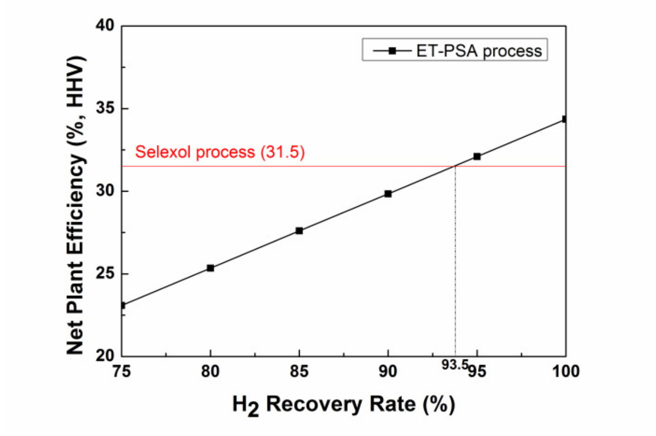

Fig. 4. Comparison of net plant efficiency of IGCC systems with Selexol process and ET-PSA process

As is shown, when the H_2 recovery rate is 100%, the gas turbine power generation of IGCC with ET−PSA process is 6.6% higher than IGCC with Selexol process, which is due to that there is no sensible heat lost in ET−PSA process. Elevated steam in the shifted gas, without being cooled and separated, directly enter the PSA subsystem, in turn enter the gas turbine subsystem. In the meanwhile, less excess air is needed to keep the gas turbine combustion temperature stay at the same, which reduces the power dissipation of air compressor. For total auxiliaries on the other hand, the power consumption of IGCC with ET−PSA process is 8.1% lower than IGCC with Selexol process. This is because there is no thermal regeneration in ET−PSA process, and pressure swing method is used to desorb the CO_2 adsorbents. The no use of thermal regeneration reduces a total amount of 19230 kWe power, which leads to a final decrease in auxiliary power of IGCC system.

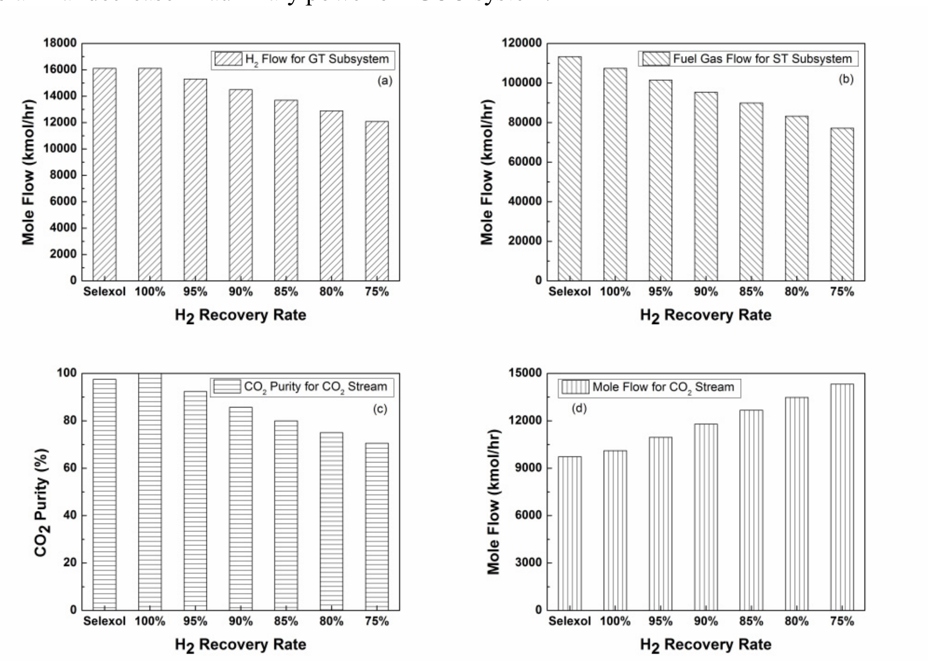

Fig. 5. Simulated results of some key parameters in IGCC systems with Selexol process and ET-PSA process (a) H_2 flow for GT subsystem; (b) Fuel gas flow for ST subsystem; (c) CO_2 purity for CO_2 stream; (d) Mole flow for CO_2 stream

However, with H_2 recovery rate of PSA subsystem decreasing from 100% to 75%, the net power and net plant efficiency sharply decreases (Fig. 3 and Fig. 4). Averagely, when the H_2 recovery rate reduces 1 percentage, the net plant efficiency of IGCC with ET−PSA process reduces 0.452 percentages. And when the H_2 recovery rate is under 93.5%, the net plant efficiency is lower than IGCC system with Selexol process. Two main reasons are considered, one is that H_2 is the main power source of gas turbine system. When H_2 recovery decreases, less amount of H_2 enters GT subsystem (Fig. 5a), therefore less amount of heat is generated in the combustor, which reduces the power exported by gas turbine. In addition, less amount of fuel gas enters the HRSG of steam turbine system (Fig. 5b), decreasing the amount of steam generated. Thus, the steam turbine power generation also reduces. The other reason is that the parameter of H_2 recovery rate is related to the flow and purity of CO_2 stream (Fig. 5c and Fig. 5d). The amount of H_2 lost in the PSA system enters the CO_2 stream, increasing the flow of CO_2 stream and power dissipation for compressing this part of gas to the desired pressure. The increase of total auxiliary power mainly depends on the increase of CO_2 compression power.

4. Conclusions

ET−PSA process with 90% of CO_2 removal rate and 99% of H_2S removal rate is built as the acid gas removal unit in a 540 MW IGCC system by Aspen Plus in the work. Compared with Selexol process, it reduces the sensible heat lost of the shifted gas and the heat lost for the thermal regeneration of absorbent/adsorbent. The main energy consumption of ET−PSA process is the H_2 lost into the CO_2 stream for rinse step. The net plant efficiency of IGCC with ET−PSA process averagely decreases 0.452 percentages with the H_2 recovery rate reducing 1 percentage. Two main reasons are considered to explain the importance of H_2 recovery rate. One is that H_2 is the main power source for gas turbine and steam turbine subsystem, the other is that H_2 lost in the PSA system enters the CO_2 stream, increasing power dissipation of CO_2 compressor.

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