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Process Synthesis with Heat Integration of Decarbonised Coal Energy Systems

Kok Siew Ng, Nan Zhang, Jhuma Sadhukhan*

Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, United Kingdom.
Jhuma.Sadhukhan@manchester.ac.uk

Development of clean coal technology is highly envisaged to mitigate the CO_2 emission level while meeting the rising global energy demands which require highly efficient and economically compelling technology. Integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS) system is highly efficient and cleaner compared to the conventional coal-fired power plant. In this study, an alternative process scheme for IGCC system has been proposed, which encompasses the recycling and re-use of CO_2 from the flue gas of gas turbine into a secondary syngas processing route, proceeding with conversion of syngas into methanol. The system modification requires extensive mass and energy integration strategies to ensure that the efficiency and economics of the system are achieved to a considerably high level. The thermodynamic and economic feasibilities of the modified IGCC system were found to attain tremendous improvements. The thermal efficiency has been increased from 54% to 89.3%, whilst the economic potential has been enhanced from 48.1 M€/y to 377.4 M€/y. These results have shown good future prospects for employing CO_2 re-use technology into IGCC system, as an alternative to CCS system.

1. Introduction

Currently, 40% of the global electricity is supplied from coal and it is expected to increase over the next few decades (World Coal Association, 2010). Coal-fired power plant is the predominant technology for generating electricity from coal, emitting approximately 2.9 Mt CO_2 per year to the atmosphere from 500 MW_e plant (IPCC, 2005). The energy and industrial sectors, including power station, manufacturing and transportation contribute to 77.9% (2005) of the global CO_2 emission, and 54.8% (2008) of the CO_2 emission in the UK (Prime et al., 2009; World Resource Institute, 2010). The CO_2 emission from coal and other solid fuels shares 25.6% of the total CO_2 emission by fuel in the UK, i.e. 531.8 Mt CO_2 in year 2008 (Prime et al., 2009). IGCC has higher efficiency than conventional coal-fired power plant through the application of cogeneration concept. IGCC is also cleaner and has high potential in capturing CO_2.

Carbon capture technologies such as pre-combustion, post-combustion and oxy-fuel combustion are prominent. Other emerging technologies are undergoing rapid development including chemical looping and oxygen transport membrane. The inclusion of carbon capture facilities normally increases the overall capital investment

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and lowers the energy efficiency of a plant (Harkin et al., 2009; Ng et al., 2010). Captured CO_2 is transported through pipelines and ships, and subsequently stored in ocean for geological formation or mineral carbonates. The series of processes of capturing, transporting and storing CO_2 is collectively known as carbon capture and storage (CCS). Other options of mitigating CO_2 emission is through CO_2 recycling and re-use. Such options include utilising CO_2 into Enhanced Oil Recovery (EOR) in oil extraction process; microalgae production; chemicals and fuels production. The question of which CO_2 mitigation options, i.e. whether to capture and store CO_2 or re-use CO_2 without capturing, is more advantageous than the others remains uncertain.

In this study, a conventional coal IGCC with CCS system has been used as the base case, which generates electricity as the main and sole product through cogeneration concept. This system can be modified into a polygeneration system, where CO_2 from the flue gas of gas turbine is re-used for syngas generation through tri-reforming process, and the syngas is subsequently converted into methanol. This system does not involve pre-capturing CO_2. Such modified system can be regarded as a dual syngas production system. These two systems with different CO_2 mitigation options are compared in terms of thermodynamic, economic and environmental performances. Additionally, heuristic-based heat integration methodology (Smith, 2005; Ng et al., 2010) has been adopted for achieving maximum energy savings from the system and thus ensuring maximum economic benefit.

2. Methodology

Flowsheet simulation in ASPEN Plus was undertaken for modelling the IGCC systems. Heat integration and economic analysis were performed in Excel, using the mass and energy balances obtained from the simulation.

2.1 Heat Integration Strategies

Important thermodynamic data such as temperature and heat duties across heat exchangers and process units were extracted from the flowsheet simulation. Screening and classifying the data were performed to ensure appropriate utilisation of heat at various levels. The heat supply and demand within the system were categorised into high and low levels based on temperature and heat duties. In other words, high temperature and / or high heat duty process units were utilised for high level tasks, i.e. steam generation, whilst low temperature and / or low heat duties process units were utilised for low level tasks, i.e. process-to-process heating or hot water generation. The composite curve analysis and energy balance were carried out to estimate the amount of steam that can be generated and the amount of steam requirement for heating. If a high level task is found to be inappropriate after performing the analysis, e.g. negligible amount of steam is generated or too much steam has to be used for heating, screening and classifying procedures were repeated and extraction of data was revised. Process stream matching and energy balance were adopted for analysing low level tasks. The proposed strategy considers a high to low level approach, since any excess heat can be used into hot water generation and this normally less likely to violate the minimum approach temperature rule. The final step is the design of utility system network (steam generation and distribution), based on the information obtained from the composite curve and energy balance analyses. Steam is generated (e.g. VHP, HP, MP and LP) and collected at various steam mains. Steam is distributed from the steam mains to process units / heat exchangers within a process site. Remaining steam from each steam main level can be expanded through steam turbine for power generation.

3. Existing and Alternative IGCC Process Schemes

3.1 Process Description

Scheme A - Coal IGCC with CCS (Figure 1 (a))

This is a conventional process scheme where coal is gasified into syngas and subsequently into heat and power via the syngas. The IGCC system under consideration has a capacity of 648.1 MW, with coal throughput of 2000 t/d. The coal slurry is fed to an entrained-flow gasifier and the process is assisted with oxygen as a gasifying medium. The syngas generated from gasification contains 28.5 mol% H_2, 18 mol% H_2O, 42.1 mol% CO, 8.4 mol% CO_2 and 3 mol% of inert gases. The syngas is cooled and undergone a series of conditioning (e.g. water-gas shift) and cleaning processes (e.g. ash, water and sulphur removal). 99% of CO_2 is assumed to be captured using pre-combustion process and stored underground. The clean syngas is then transferred to the gas turbine for electricity generation. The exhaust gas from the gas turbine consists of 6 mol% CO_2, 28 mol% H_2O and 66 mol% inert gases.

Scheme B - Coal IGCC with tri-reforming and methanol synthesis (Figure 1 (b))

An alternative process scheme for IGCC has been proposed, using the same capacity as Scheme A, i.e. coal throughput of 2000 t/d (equivalent to 648.1 MW). The proposed scheme requires a major modification on the conventional IGCC system, where the original cogeneration system with heat and power generation is transformed into polygeneration into methanol as an additional product. This involves the utilisation of CO_2 from the exhaust gas of gas turbine as the feedstock for tri-reforming process (equations (1)-(3)) (Song, 2001; Song and Pan, 2004), which is further converted into syngas. The exhaust gas from the gas turbine contains 64 mol% CO_2, 34 mol% H_2O and 2 mol% inert gases. This modified system can be visualised to have dual syngas processing routes, where the first route is aimed at electricity generation, whilst the second route is targeted for methanol production. Tri-reforming of methane process was first implemented by Song in 2001 as a potential method to utilise CO_2 into the production of valuable syngas at desired ratio and reduce or eliminate carbon formation on catalyst (Song, 2001; Song and Pan, 2004). Tri-reforming process is operated at 1 bar and 850°C, fed with CH_4, CO_2, H_2O and O_2 at a ratio of 1: 0.475: 0.475: 0.1 (Song and Pan, 2004). The syngas produced from tri-reforming process comprises of 59 mol% H_2, 3 mol% H_2O, 36 mol% CO and 2 mol% CO_2, thus having a H_2/CO molar ratio of 1.6.

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \qquad \Delta H_R^\circ = +247.3\ \text{kJ/mol} \qquad (1)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H_R^\circ = +206.3\ \text{kJ/mol} \qquad (2)$$

$$CH_4 + 0.5O_2 \leftrightarrow CO + 2H_2 \qquad \Delta H_R^\circ = -35.6\ \text{kJ/mol} \qquad (3)$$

This scheme demonstrates a system with CO_2 re-use from flue gas without pre-captured. CO_2 is not captured this time, but separated from H_2 via pressure swing adsorption process. It has been assumed that 98% by mole of H_2 can be separated from the product gas stream (from gasification) and combined with the product gas from the tri-reforming process. This has eliminated the use of water-gas shift reactor, if the stoichiometric of the product gas can be adjusted through the manipulation of the feedstock and operating condition of the tri-reforming process. In spite of the reduction of capital cost for water-gas shift reactor, this modification also prevents CO_2 generation from the water-gas shift reaction. The remaining syngas from gasification after separating H_2 contains significant amount of CO and CO_2, which is then used for power generation via gas turbine. A small amount of natural gas may be needed to manipulate the Wobbe Index of the gas turbine, since only small amount of H_2 is present in the inlet gas to the gas turbine combustor. Oxygen instead of air is used in the gas turbine combustor for avoiding further dilution of the fuel gas by nitrogen, and also to avoid accumulation of nitrogen in the downstream process (tri-reforming and methanol synthesis) which causes increase in capital cost. This is the oxy-fuel combustion concept and it has advantages such as concentrating the CO_2 in the exhaust gas stream and reducing NO_x emission (Figueroa et al., 2008). Methanol reactions take place at 100 bar and 250°C, requiring a feed with $(H_2-CO_2)/(CO+CO_2)$ of 2. 95% by volume of unreacted offgas from methanol synthesis is recycled to enhance the production of methanol, while 5% of the offgas is purged. Liquid methanol was sent to distillation units, where 99.5% by weight of methanol can be recovered.

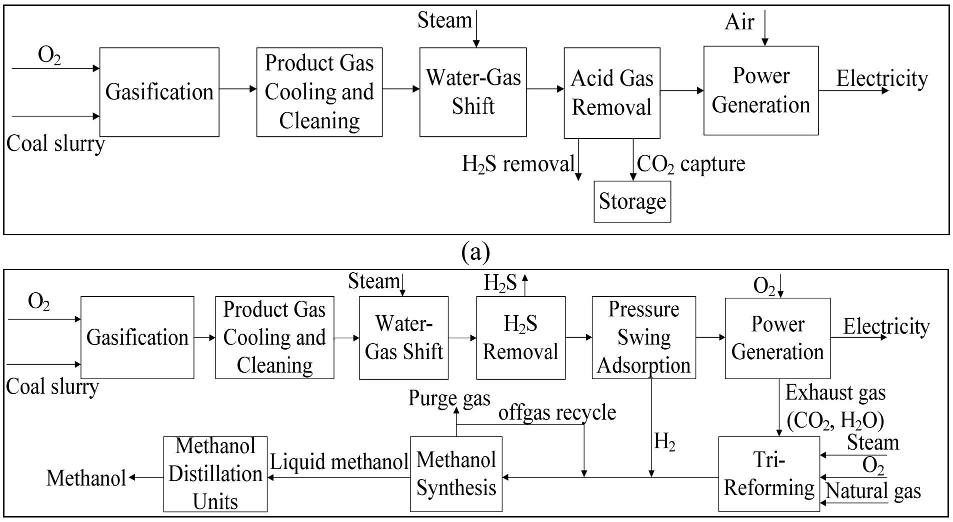

Figure 1: (a) Scheme A: Coal IGCC with CCS; (b) Scheme B: Coal IGCC with tri-reforming and methanol synthesis.

3.2 Performance Analysis

The performances of the existing and alternative IGCC process schemes, with respect to thermodynamic efficiency and economic potential are evaluated and compared, in Tables 1 and 2, respectively.

Table 1: Efficiency analysis.

Process Scheme	Scheme A	Scheme B
Product	LHV (MW)	
1. Electricity	349.7	229.7
2. Methanol	-	2852.8
Total LHV of products	**349.7**	3082.5
Feed	LHV (MW)	
Main feedstock	Coal	Coal
LHV of main feedstock	648.1	648.1
Additional feedstock	-	Natural gas
LHV of additional feedstock	-	2802.6
Total LHV of feedstock	**648.1**	**3450.7**
Thermal efficiency based on LHV of feedstock (%)	**54.0**	**89.3**

Table 2: Economic analysis.

Process Scheme	Scheme A	Scheme B
Capital cost (M€/y)	91.4	145.6
Operating cost (M€/y)	67.9	655.6
Value of products (M€/y)	207.4	1178.6
1. Electricity	207.4	136.3
2. Methanol	-	1042.3
Economic Potential (M€/y)	48.1	377.4

In terms of environmental impact, 44.7 t/h of CO_2 is emitted and 141.9 t/h of CO_2 is captured from the system in Scheme A, while 52.1 t/h of CO_2 is emitted from the system in Scheme B.

4. Discussion

From the results presented in section 3.2, the transformation of cogeneration system into polygeneration system shows promising outcome, with an improvement in efficiency from 54% (Scheme A) to 89.3% (Scheme B) (Table 1). The modification also involves an expansion of the system to introduce a secondary syngas processing route, and the capacity is increased from 648.1 MW to 3450.7 MW, where natural gas has been added as an additional feedstock in tri-reforming process. The advantage of Scheme B is that substantial amount of methanol is produced for which it can increase the overall value of products, while the disadvantage is additional utilisation of natural gas in tri-reforming process which leads to increases in capital and operating costs. Nevertheless, this does not drag down the economic potential of such system. In fact, the economic potential has been raised by 7.8 times through this modification, i.e. 48.1 M€/y (Scheme A) compared to 377.4 M€/y (Scheme B) (Table 2). Furthermore, the CO_2 emission per unit product in Scheme B, 16.9 t CO_2/GWh, is lower than that in Scheme A, 127.8 t CO_2/GWh. These imply 86.8% reduction in the greenhouse gas emissions and that Scheme B is a successful modification and thermodynamically, economically and environmentally sound compared to an equivalent coal IGCC system with CCS.

5. Conclusions

Re-using CO_2 can be beneficial in reducing the amount of CO_2 that needs to be captured, and also the process economics of a system can be enhanced through the generation of additional product. The overall modification and design strategy of the system as well as the mass and energy integration of overall systems are highly essential in synthesising a highly efficient, economically appealing and environmentally benign system.

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