Modelling and simulation of a biomass-based integrated gasification combined cycle with carbon capture: comparison between monoethanolamine and potassium carbonate

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Abstract. There are global efforts to reduce the impacts from climate change by limiting increases in temperature to 1.5 °C until 2030, and achieve carbon neutrality by 2050. Thus, it is necessary to design new neutral processes and systems that can meet the varying and growing demands of the population in terms of energy, water and food. One of the main carbon emitters and contributors to climate change is the energy industry, which primarily uses oil and natural gas as an energy source. Fortunately, alternative resources are available such as renewable energies that assemble various environmental and economic benefits. However, more work is necessitated to efficiently utilise these resources by designing, analysing, and optimising existing and new renewable energy-based processes. Therefore, this study proposes a net negative carbon emissions energy system that utilises waste biomass as a feedstock. A biomass based integrated gasification combined cycle combined with a post combustion carbon capture unit by means of chemical absorption is designed and analysed. Two different chemical solvents are used for comparison: Monoethanolamine (MEA) and potassium carbonate. The proposed integrated system is modelled and simulated in Aspen Plus software, and is analysed thermodynamically in terms of energy and exergy efficiencies. A sensitivity analysis is also conducted to assess the effect of varying operating conditions such as flowrate, and temperature of the lean solvent, and the pressure inside the stripper. At design conditions with 80% carbon capture, the system generates 419 kW of electricity and operates at -0.32 kg/kWh of CO₂ for both the potassium carbonate and MEA systems.

Keywords: Biomass, BIGCC, BECCS, Aspen plus, carbon capture, MEA, potassium carbonate

1. Introduction
The rapid population growth and economic development propelled an increase in the global energy demand. The US Energy Information Administration (IEA) reported that energy consumption will witness a substantial rise, nearly 50% between 2018 and 2050 (1). The energy sector is considered as the sector with the highest impact on global warming, being accountable for two thirds of the total greenhouse gases, and 80% of the total CO\(_2\) emissions released globally (2). CO\(_2\) is considered a main contributor to anthropogenic greenhouse gas emissions incipient from activities related to burning fossil fuels. In fact, CO\(_2\) levels in the atmosphere are on the rise since the mid-1800s following the industrial revolution, and are 40% higher in 2018 reaching concentrations of approximately 400 ppm (3). These emissions induced a continuous build-up of greenhouse gases resulting in a warming effect, increasing the temperature level by 0.2°C per decade, reaching an accumulated 1°C increase in global surface temperature in 2017 compared to the pre-industrial era (4). Hence, mitigation and adaptation pathways are necessary to reduce negative emissions and combat climate change. Attaining neutral CO\(_2\) emissions neutrality development is one way to mitigate global warming. In fact, in one of the scenarios assessed in the 5th Assessment Report by the Intergovernmental Panel on Climate Change, the ambitious target of reaching a level of 450 ppm of CO\(_2\)-eq (corresponding to 2°C increase in temperature) by the year 2100, can be achieved through a substantial decrease of emissions from the energy sector, approximately 90% of CO\(_2\)-eq between 2040 and 2070 as compared to the 2010 baseline. This can be achieved through increasing the utilisation of low energy supply technologies to a share of 80% by 2050, from which bioenergy with carbon capture and storage (BECCS) represents a promising technology as it achieves carbon negative carbon emissions (5). However, this technology is currently in the development stage in which biomass availability, economic feasibility, land allocation and food security are important factors that are considered in such schemes (6). Hence, it is necessary to study the existing interlinkages between energy, water and food in implementing greenhouse gas control technologies for biomass based energy systems (7). In parallel, further research and development is needed in order to successfully implement the technology on a larger scale. For instance, research is underway to lower the energy penalty from the carbon removal process, and to further enhance the economic feasibility of the process (8). The scientific community demonstrated the potential of the Integrated Gasification Combined Cycle (IGCC) technology with the integration of various carbon capture technologies and methods. By studying the combined system, researchers were able to reach higher efficiencies through the utilization of wastes within the system (9,10).

Carbon capture can be applied either in the pre-combustion, oxy-fuel combustion, or post combustion phase. There are several carbon separating methods such as absorption, membrane separation, adsorption, chemical looping, cryogenic distillation, etc. Amongst these methods, chemical absorption is known as the most feasible and mature solution in many applications. It is based on removing CO\(_2\) by means of a liquid sorbent such as Monoethanolamine (MEA), Diethanolamine (DEA), potassium carbonate, and Piperazine (9). In fact, several studies conducted a comparison between different sorbents, and found that MEA performed better compared to others (11,12). Although this solvent has shown promising results and good CO\(_2\) removal rates, one important challenge to consider is the amine degradation causing corrosion in the columns, in addition to its environmental impact due to the generation of volatile compounds. Hence, it is crucial to investigate other solvent for CO\(_2\) separation by chemical absorption. Potassium carbonate is also considered as a possible sorbent for CO\(_2\) separation, and is particularly beneficial because of its low toxicity and low degradation as compared to MEA. However, the slow kinetic reactions of this solvent with CO\(_2\) pose a major obstacle for using this separation method (13). Moreover, more research is needed to further investigate the performance of these solvents particularly within BECCS technologies and systems.

The aim of this study is to assess the technical performance of two different solvents, MEA and potassium carbonate, for chemical absorption of CO\(_2\) from a biomass fed integrated gasification combined cycle application. Potassium carbonate is considered a possible substitute of MEA, suppressing many of its drawbacks, however a detailed study is needed to compare their thermodynamic performance for BECCS application. Hence, this study directly questions related to whether potassium carbonate can achieve MEA performance, and be an environmentally friendly alternative solution for
BECCS technology. The technical performance is assessed through calculating the overall energy and exergy efficiencies of the integrated system for both cases; using MEA and K$_2$CO$_3$ as solvents. A sensitivity analysis is also conducted to see the effect of changing operating parameters.

2. System Description

In this study a biomass based integrated gasification combined cycle (BIGCC) coupled with post-combustion carbon capture is presented. Chemical absorption is used as a CO$_2$ separation method by means of two separate solvents, Monoethanolamine (MEA), and potassium carbonate (K$_2$CO$_3$). The two solvents are used in two distinct models for comparison purposes. The system can be divided into three segments; gasification, power plant and carbon capture. Date pits are used as a biomass feedstock, the ultimate and proximate analyses are taken from literature (14). In the first unit, a steam gasification process occurs to convert biomass to syngas. The gasification process is optimised for maximum syngas production and an operating temperature of 850 °C is selected based on earlier findings (15). Syngas is then passed to the second unit of the integrated system for power generation. The first process the syngas undergoes is cooling in order to reach an applicable temperature for compression. The recovery of the syngas heat is the main advantage of using the integrated gasification combined cycle. This heat is recovered using a waste heat recovery unit to supply the required steam to the dual-pressure steam turbine. Subsequently, the cooled syngas is compressed and is sent to the combustion chamber along with compressed air. The output combusted gas is used then expanded in the gas turbine for power generation. The heat from the exhaust stream of the gas turbine is also recovered to supply the required heat for the dual-pressure steam turbine. After heat recovery the exhaust gas from the gas turbine, having a CO$_2$ content of 16% wt, is fed to the carbon capture unit. This CO$_2$ amount is suitable for post-combustion CO$_2$ removal. In the carbon capture unit, the exhaust gas is fed to the bottom stage of the absorber and the lean solvent is fed to the upper stage, creating a countercurrent flow. The CO$_2$ rich stream exiting the absorber is then served in the top stage of the stripper.

3. Modelling and Simulation

A rigorous modeling and simulation study is conducted for the BIGCC coupled with post-combustion carbon capture using Aspen Plus software. The system is simulated under thermodynamic equilibrium conditions for the BIGCC segment, and a rate-based model for the carbon capture unit. A rate-based model is essential to account for the slow rate reactions between the solvent and CO$_2$ especially for the K$_2$CO$_3$ case. For comparison purposes, both MEA and K$_2$CO$_3$ models were run under this model. The assumptions considered in the model; steady state, isothermal and atmospheric conditions, tar formation is neglected, and char is regarded as 100% carbon. The Peng Robinson model with Boston-Mathias modifications is used for the calculation of the physical properties for the BIGCC unit. As for the carbon capture unit, an Electrolyte Non-random Two Liquid (NRTL) model with Redlich-Kwong equation of state is adopted. A RadFrac model is used for both the absorber and the column, which takes into consideration the kinetics of the reactions. The CO$_2$ removal reactions by MEA and K$_2$CO$_3$ involve equilibrium and kinetic reactions. The forwards and backward kinetic reactions are shown by equations (1) and (2) for MEA and equations (4) and (5) for K$_2$CO$_3$.

\[
\text{MEA} + \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{MEACOO}^- + \text{H}_3\text{O}^+ \quad (1)
\]
\[
\text{CO}_2 + \text{OH}^- \leftrightarrow \text{HCO}_3^- \quad (2)
\]

The overall reaction of K$_2$CO$_3$ is represented by equation (3).

\[
\text{K}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow 2\text{KHCO}_3 
\]

\[
\text{HCO}_3^- + \text{H}_2\text{O} \leftrightarrow \text{CO}_3^{2-} + \text{H}_3\text{O}^+ \quad (4)
\]
\[
\text{CO}_2 + \text{OH}^- \leftrightarrow \text{HCO}_3^- \quad (5)
\]
The kinetics are calculated following the Aspen Plus built-in Power Law expressed in equation (6).

\[ \text{Kinetic factor} = kT^n \left( e^{\frac{E}{RT}} \right) \] (6)

The overall energetic and exergetic efficiencies are calculated as shown in equations (7) and (8) respectively.

\[ \eta_{en} = \frac{\dot{W}_{\text{net}} + \dot{m}_{\text{CO}_2} h_{\text{CO}_2}}{\dot{m}_{\text{biomass}} h_{\text{biomass}} + \dot{Q}_{\text{heater}} + \dot{Q}_{\text{reboiler}}} \] (7)

\[ \eta_{ex} = \frac{\dot{W}_{\text{net}} + \dot{m}_{\text{CO}_2} h_{\text{CO}_2}}{\dot{m}_{\text{biomass}} e_{\text{biomass}} + \dot{Q}_{\text{heater}} (1 - \frac{T_0}{T_2^2}) + \dot{Q}_{\text{reboiler}} (1 - \frac{T_0}{T_2^2})} \] (8)

Where \( \dot{W}_{\text{net}} \) represents the work net from the BIGCC, \( \dot{m}_{\text{CO}_2} \) and \( \dot{m}_{\text{biomass}} \) are the mass flow rates of \( \text{CO}_2 \) removed biomass respectively. \( h_{\text{CO}_2} \) and \( h_{\text{biomass}} \), \( e_{\text{CO}_2} \) and \( e_{\text{biomass}} \) represent the enthalpies and total exergies of the \( \text{CO}_2 \) captured and biomass respectively. \( \dot{Q}_{\text{heater}} \) is the heat duty of heaters used for steam generation throughout the system, and \( \dot{Q}_{\text{reboiler}} \) is the reboiler heat duty needed for vapor generation in the stripper and solvent regeneration.

4. Results and Discussion

For this study date pits are used as a biomass feed at a rate of 100 kg/hr. Gasification is an important unit in this study, because it affects the amount of syngas produced and the power generated. A sensitivity analysis is run to assess the effect of gasification temperature on power and \( \text{CO}_2 \) amount in the exhaust gas from the gas turbine. The power increases with increasing temperature and starts to stagnate beyond 850°C. Thus, a temperature of 850°C is selected as the optimal gasification temperature, generating 420 kW of power and an exhaust gas containing a \( \text{CO}_2 \) content of 16% wt. The energy efficiency of the BIGCC reaches 48% and exergy efficiency is 60.6%.

The flowrate and composition of biomass tightly affects the solvent flowrate. Hence, with a higher exhaust gas flowrate and a higher \( \text{CO}_2 \) composition, more solvent is required to absorb the \( \text{CO}_2 \). A comparison between MEA and \( \text{K}_2\text{CO}_3 \) was conducted based on 80% \( \text{CO}_2 \) removal rate. The 30% wt MEA based system accounted for the highest reboiler heat duty of about 4646 kJ/kg of \( \text{CO}_2 \) as compared to the 40% wt \( \text{K}_2\text{CO}_3 \) based system where the reboiler heat duty was noted as 3300 kJ/kg of \( \text{CO}_2 \). For the MEA system the main obstacle is the degradation of the amine when increasing the operating temperature, which prohibits the enhancement of the kinetics of the reactions occurring. Therefore, enhancing this system is necessary at the cost of the reboiler duty. Hence, using \( \text{K}_2\text{CO}_3 \) as a solvent can decrease the energy required for regenerating the solvent by 29% as compared to MEA. The reboiler duty represents the major energy input to the carbon capture unit system, thus directly impacting the efficiencies. The overall energy and exergy efficiencies of the overall BIGCC + carbon capture process were found for MEA as 39.1% and 47.9% and for \( \text{K}_2\text{CO}_3 \) as 42.2% and 49.5% respectively. Moreover, with 80% \( \text{CO}_2 \) removal, the integrated system, either using MEA or \( \text{K}_2\text{CO}_3 \) as a solvent, runs at an environmental cost of negative 0.32 kg/kWh of \( \text{CO}_2 \). Moreover, the effects of lean temperature and flowrate are studied for the two systems. For the MEA system, as the temperature of the solvent increases the \( \text{CO}_2 \) removal percentage slightly decreases as shown in figure (1). When the solvent temperature is high, less heat needs to be supplied to the reboiler to generate vapor for \( \text{CO}_2 \) stripping. Since the stripping of \( \text{CO}_2 \) in the MEA system is temperature swing driven, it means that the stripper needs higher temperatures. Hence, the higher the lean temperature the less heat needed by the reboiler in the stripper. The effect of the lean flowrate is also studied to determine the required amount for 80% \( \text{CO}_2 \) removal rate as shown in figure (2). Passed a lean flowrate of approximately 1500 kg/h the \( \text{CO}_2 \) removal rate slightly decreases, hence more reboiler heat duty is required to achieve a better \( \text{CO}_2 \) removal rate. In increasing the flowrate, the sizing of the absorber and stripper needs to be adjusted accordingly to
prevent any flooding. This also represents a major tradeoff between the technical performance and the economics of the columns.

**Effect of lean temperature for MEA system**

For the K$_2$CO$_3$ system, as the solvent temperature increases the CO$_2$ removal rate decreases as illustrated in figure (3). Hence, a maximum CO$_2$ removal rate can be attained at a relatively low temperature. Moreover, the increasing lean temperature impacts the reboiler heat duty. It is observed that the reboiler heat duty is decreased with decreasing CO$_2$ removal rate. Thus, there is a tradeoff between improving the CO$_2$ removal rate while achieving the lowest reboiler heat duty. The pressure drop inside the stripper is also an important factor for the K$_2$CO$_3$ because the stripping process is pressure swing driven in this system. Hence, in the K$_2$CO$_3$ system the stripper is considered as the critical component as opposed to the MEA system. Therefore, the rich loading entering at the top of the stripper needs to have a lower pressure as compared to the MEA. A sensitivity analysis is conducted to assess the effect of the stripper pressure drop on the CO$_2$ removal rate and reboiler heat duty, and a pressure drop of 10 mbar was chosen to achieve the required CO$_2$ removal as shown in figure (4).

**Effect of lean temperature for K$_2$CO$_3$ system**

**Effect of stripper pressure drop for K$_2$CO$_3$**

5. **Conclusion**

CO$_2$ emissions from fossil fuel based power plants can be reduced through BECCS technology, whereby high energy efficiencies and negative CO$_2$ emissions can be attained. As such, this study presented a BIGCC system with post-combustion carbon capture. It includes CO$_2$ removal which is explored by means of chemical absorption, where two solvents are compared. The use of MEA as a solvent in this
application is a mature and commercial solution. However, it is degradable and can cause economic and environmental damages. Hence, K₂CO₃ can be a viable alternative because of its environmental benefits and low cost. For an 80% CO₂ removal, it was found that K₂CO₃ had a lower reboiler heat duty by 29% than MEA, and thus less energy input is required by this system. This was noticeably reflected on the energetic and exergetic efficiencies of the integrated system, where the K₂CO₃ system reached 47.9% and 49.5% and MEA 39.1% and 42.2% energy and exergy efficiencies respectively.

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