

Simulation and analysis of carbon capture process using piperazine for large scale biomass-fired power plant

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ABSTRACT

Environmental concerns caused by CO₂ emissions has attracted much attention by researchers worldwide. CO₂ can be captured from large single sources such as power plants to reduce the CO₂ emission. Solvent-based post-combustion carbon capture (PCC) process for large scale biomass-fired power plant could achieve negative carbon emission. However, capture level is commonly set at 90% in many studies. The small fraction of residual CO₂ is still a large amount due to the high flue gas flowrate. In this study, a piperazine-based PCC process at 95% capture level for biomass-fired power plant was studied. The process was simulated in Aspen Plus® V11, validated and scaled up. The energy performance results showed that when the capture level is increased to 95%, the reboiler duty rises to 4.07 GJ/tCO₂, corresponding to an increase of approximately 13.7% compared to the 90% case. This additional regeneration energy demand is offset by the reduction in residual CO₂ emissions from flue gas or 0.23 million tons extra CO₂ captured each year (from 3.86 million tons CO₂/year to 4.09 million tons CO₂/year). It is feasible for improving negative emission performance in BECCS systems. More analysis (e.g. different configurations and economic analysis) will be performed to further discuss the high capture level process.

Keywords: carbon capture, chemical absorption, process simulation, technical assessment, negative emission technologies

1. INTRODUCTION

1.1 Background and motivation

Biomass energy with carbon capture and storage (BECCS) has been widely recognized as a negative emission technology in which renewable energy generation is combined with permanent removal of atmospheric carbon dioxide. BECCS is increasingly considered as an essential component in long-term carbon emission reducing strategies.

From process engineering, the effectiveness of BECCS is mainly dependent on the efficiency of the solvent-based PCC system. While a capture level of 90% is commonly adopted in PCC studies from the IEA report [1], the remaining CO₂ in the treated flue gas still represents a direct emission to the atmosphere. Reducing the residual CO₂ concentration through higher capture levels becomes increasingly relevant for BECCS applications that aim to achieve meaningful negative emissions.

1.2 Literature review

The solvent-based PCC is widely used from Wang et al. [2]. The process is based on chemical absorption to capture CO₂ from the flue gas. In most system studies, a capture level of 90% is typically adopted as the default design point. It avoids the steep energy penalty and equipment scale-up associated with very high capture level. In Canepa et al. [3], MEA-based PCC process for combined cycle gas turbine (CCGT) power plant was studied under 90% capture level. Exhaust gas recirculation (EGR) technology was proposed to reduce the flue gas flowrate to solvent-based PCC plant, therefore reducing sizes of key equipment (mainly absorber) energy consumption for solvent regeneration. Luo and Wang [4] analysed the solvent-based PCC for nature gas combined cycle (NGCC) power plant. They found that carbon capture becomes economically justified only when the carbon price exceeds about €100–120 per ton CO₂. Higher fuel and CO₂ transport costs will further increase the required carbon price to maintain high capture levels. Hu et al. [5] applied the PCC using MEA for treating flue

gas from thermal cracking furnace in ethylene manufacturing under the same capture level. Through integrating excess process heat can supply regeneration energy and reduce CO₂ capture cost from about \$80/tCO₂ to \$70/tCO₂.

Study of Michailos and Gibbins [6] explored solvent-based PCC process to facilitate 95–99% capture level from CCGT flue gas. The results show that there are significant differences in performance and energy consumption under different capture levels. The increasing capture level above 90% is technically possible but often comes with higher costs and higher energy consumption used, especially for post-combustion systems. Many studies historically capture level around 85–90%, leaving residual emissions uncaptured.

BECCS studies commonly treat solvent-based PCC as a key enabling block. IEAGHG has discussed higher capture rates for biomass as a method for lower residual emissions, while also noting that solvent-based PCC can face a high cost and energy penalty as capture level increases beyond typical benchmarks. More recent work has started to examine biomass-fired power plant with PCC configurations and solvent choices in more detail. For example, Ren et al. [7] investigated techno-economic performance and optimisation of piperazine-based PCC and CO₂ compression for large-scale supercritical biomass-fired power plants, discussing solvent choice and configuration effects specifically for biomass contexts.

1.3 Novelty of this study

Several studies on the solvent-based PCC process under 90% capture level has been discussed in the literature review section. For large-scale biomass-fired power plants, even a relatively small fraction of residual CO₂ can translate into a substantial emission due to the high flue gas flow rate. For the flue gas from a 550 MW biomass-fired power plant, increasing the capture level from 90% to 95% raises the daily amount of captured CO₂ nearly 700 tonnes. The capture cost of DAC commonly exceeds USD 600 per tonne. This additional captured amount shows great potential. Within this context, a capture level of 95% sets as the critical engineering setting. It could reduce the residual CO₂ emissions compared with the widely adopted 90% level, while remaining within a range that may still be technically achievable using advanced solvents and well-designed solvent-based PCC systems. The energy performance of solvent-based PCC process operating at such high capture levels has not been systematically assessed for biomass-fired power plants.

2. PROCESS DESCRIPTION

In this study, a standard solvent-based PCC process is considered for application to a large-scale biomass-

fired power plant. The process configuration follows a conventional closed-loop absorption–regeneration system using piperazine (PZ) as the reactive solvent and is representative of industrial PCC designs targeting high CO₂ capture level. The flowsheet diagram of solvent-based PCC is shown in the Figure 1.

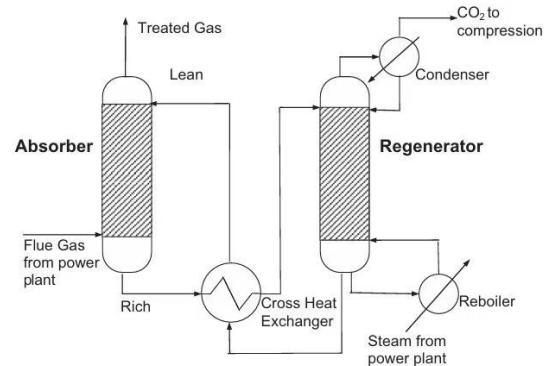


Figure 1. The process of standard PCC process from Lawal et al. [8]

The overall process consists of an absorber, a stripper equipped with a reboiler, solvent circulation pumps, and a set of heat exchangers for temperature control and heat recovery. Flue gas exiting the biomass-fired power plant is introduced at the bottom of the absorber. As Lawal et al. [8] and Otitoju et al. [9] mentioned, the gas flows upward through the packed bed, where it comes into counter-current contact with lean PZ solvent introduced at the top of the column. CO₂ is removed from the flue gas through combined gas–liquid mass transfer and chemical reaction with the solvent, resulting in a treated gas stream with reduced CO₂ concentration leaving the top of the absorber.

The CO₂-rich solvent collected at the bottom of the absorber is pumped to the regeneration section. Steam generated in the reboiler raises the temperature of the solvent, reversing the absorption reactions and releasing CO₂ from the liquid phase. The regenerated lean solvent exits the bottom of the stripper and is routed back to the absorber after cooling.

The solvent used in this study is 30 wt% PZ. Relative to MEA, PZ exhibits higher CO₂ absorption capacity and faster reaction kinetics, allowing operation at higher rich loadings. PZ solvent has better performance when targeting high capture levels, as they reduce the extent of solvent circulation and absorber height required to achieve a given removal target.

3. MODEL DEVELOPMENT, MODEL VALIDATION AND SCALE-UP

3.1 Model development

In this study, the DAC process using PZ was developed in Aspen Plus® V11. The absorber and stripper are all rate-based models using RadFrac Block in the software. The reactions and physical properties used for rate-based model was the same as Otitoju et al. [9]. The details are not shown here due to page limit.

3.2 Model validation

The developed PCC model was validated by pilot-scale experimental data. The experimental cases were chosen from the pilot plant experimental results in the University of Texas at Austin from Otitoju et al. [9]. The flue gas conditions were stabled as 0.165 m³/s and 12 vol% of CO₂ in flue gas. The pilot plant consists of a packed-bed absorber and stripper equipped with structured packing. The absorber was designed as packed columns with a diameter of 0.427 m and a total height of 6.1 m. The column contained two 3.05 m sections of Mellapak 2X packing. In the present study, Mellapak 2X packing was selected in the simulation [7].

Model validation used five experimental cases operated under different conditions. These cases were selected with different operating parameters, including variations in liquid-to-gas (L/G) ratio, lean solvent loading, and solvent circulation rate from Dugas [10]. The CO₂ capture level was selected as the primary output variable for validation. For each experimental case, the simulated capture level was compared with the corresponding experimental value, and the relative error was calculated. As shown in the Figure 2, across the five validation cases, the relative error between model prediction results and experimental data remained within ±10%. This level of agreement indicates that the rate-based model can simulate the CO₂ absorption process with reliability. The validation results therefore support the use of the developed model for subsequent scale-up and high capture level analysis.

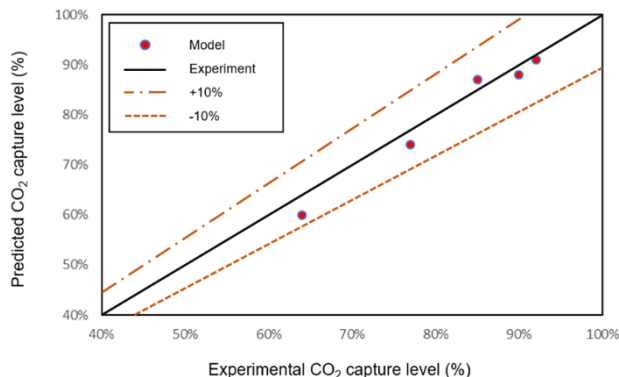


Figure 2. Experimental data versus level model prediction for CO₂ capture level for the 5 experimental cases

3.3 Model scale-up

Following model validation at pilot scale, the PCC

model was scaled up to deal with the flue gas from a large biomass-fired power plant with an electrical output of 550 MW. The solvent composition was maintained at 30 wt% PZ. The scale-up of the absorber and stripper was performed using established packed-column scale up design principles. The absorber diameter was determined based on flue gas flowrate as 647.5 kg/s and hydrodynamic constraints using the Generalized Pressure Drop Correlation (GPDC) [9]. This approach makes sure that column operation remains below flooding limits while maintaining acceptable pressure drop under large flue gas flowrates from biomass-fired power plants.

Table 1 presents the dimensions of the absorber and stripper calculated using the GPDC method and compares the cases operating at 90% and 95% capture levels. As shown in the Table 1, increasing the capture level requires the absorber to remove a larger fraction of CO₂ from the flue gas. To achieve this, a higher solvent circulation rate and a longer effective contact time between the gas and liquid phases are required, which leads to an increase in absorber size compared with the 90% capture case. The higher solvent flow rate also results in an increased regeneration demand, which in turn increases the required size of the stripper.

Table 1: Comparison of 90% capture level scale up simulation results with 95%

Scale up results	90% capture level	95% capture level
Absorbers		
Diameter (m)	10.4	11.9
Packing height (m)	25	28
Stripper		
Diameter (m)	8	10
Packing height (m)	20	20

4. SENSITIVITY ANALYSIS

The influence of lean solvent loading on the energy performance of the PZ-based PCC process was analysed using the validated standard PCC model. Two capture levels, 90% and 95%, were considered in order to examine how the operating strategy affects reboiler duty under different removal targets. For each capture level, the lean loading was varied with same specified overall CO₂ capture level.

As shown in Figure 3, the reboiler duty exhibits the relationship with lean loading for both capture levels. At relatively low lean loading, deeper solvent regeneration is required to maintain the target CO₂ removal, which leads to a higher reboiler duty. As lean loading increases, the regeneration requirement is gradually relaxed, resulting in a decrease in reboiler duty. However, beyond a certain lean loading range, further increases in lean loading cause the reboiler duty to rise again. This trend can be

explained by the corresponding change in solvent circulation rate. Figure 4 shows that the solvent flow rate increases continuously with increasing lean loading for both capture levels. At higher lean loading, a larger solvent circulation rate is required for same CO₂ removal efficiency, as the driving force for absorption in the absorber is reduced. The increased circulation rate leads to higher sensible and latent heat requirements in the regeneration section, which offsets the benefit of reduced regeneration depth and results in an overall increase in reboiler duty.

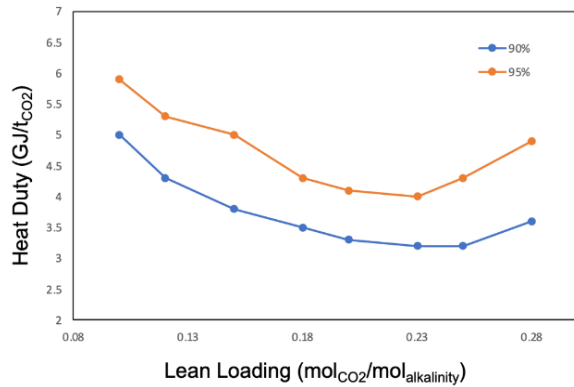


Figure 3. Energy consumption at various lean loadings for different capture level (%)

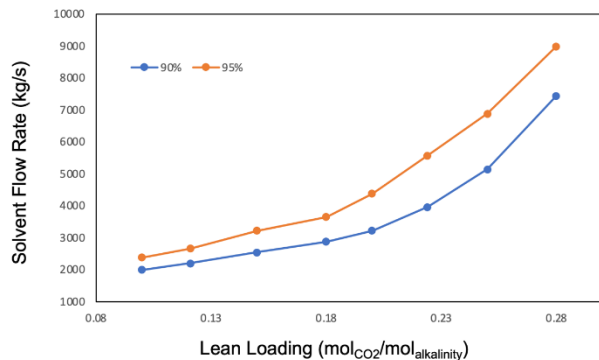


Figure 4. Solvent flow rate at various lean loading for different capture level (%)

For the 90% capture case, the minimum reboiler duty of approximately 3.5 GJ/tCO₂ is achieved at a lean loading of around 0.22–0.24 mol CO₂/mol alkalinity. A similar trend is observed for the 95% capture case, although the reboiler duty becomes higher across the entire lean loading range due to the higher regeneration requirement. The minimum reboiler duty for the 95% capture case is approximately 4.0 GJ/tCO₂, occurring at a similar lean loading range.

Comparing these two capture levels, the results showed that increasing the capture level from 90% to 95% systematically shifts the energy performance curve upward. This is attributed to the combined effects of

deeper solvent regeneration and higher solvent circulation rates required at the higher capture level.

Overall, the sensitivity analysis shows that lean loading is important in determining the regeneration energy demand of the PCC process using PZ. An optimal lean loading range exists where the trade-off between regeneration depth and solvent circulation is balanced. Although operating at 95% capture inevitably increases the reboiler duty, the additional energy requirement remains moderate within the identified optimal lean loading range, supporting the feasibility of high capture operation in BECCS applications.

5. RESULTS FROM ENERGY ASSESSMENT

The energy performance of the PZ-based PCC process was evaluated by comparing operation at 90% and 95% CO₂ capture levels. The specific reboiler duty, expressed in GJ/tCO₂, was used as the primary performance indicator, as solvent regeneration represents the dominant energy consumption in the process.

Figure 5 presents the variation of reboiler duty with capture level. At a capture level of 90%, the reboiler duty is 3.58 GJ/tCO₂ [7]. When the capture level is increased to 95%, the reboiler duty rises to 4.07 GJ/tCO₂, corresponding to an increase of approximately 13.7%. This result confirms that achieving higher CO₂ removal requires additional thermal energy for solvent regeneration.

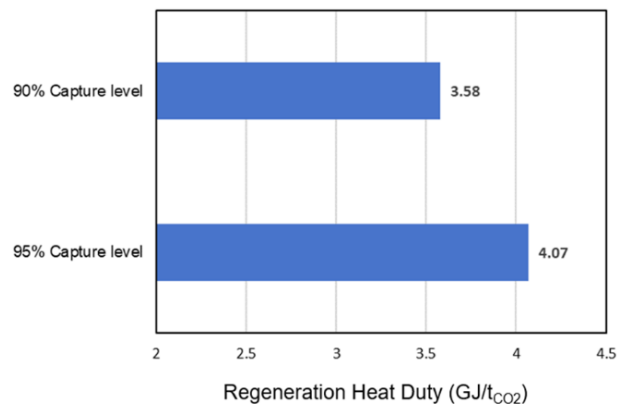


Figure 5. Regeneration heat duty of different configurations of PCC processes using PZ

From a process perspective, the increase in reboiler duty can be explained by the combined effects of deeper solvent regeneration and changes in column operation. To achieve a higher capture level, the lean solvent leaving the stripper must reach a lower CO₂ loading, which directly increases the thermal requirement in the reboiler. At the same time, the absorber must provide sufficient contact time and solvent capacity to remove a larger

fraction of CO₂ from the flue gas. This is reflected in the increased absorber dimensions and solvent circulation rates observed for the 95% capture case compared with the 90% case. The higher solvent circulation rate required at 95% capture also affects the regeneration section. An increased liquid flow to the stripper leads to a larger stripper size and higher sensible and latent heat demands during regeneration. These effects together contribute to the observed increase in reboiler duty. The results showed that higher capture efficiency can be achieved, but with the increasing cost of regeneration energy demand.

Despite this increase, the additional energy requirement is still acceptable. For the flue gas from the 550MW biomass-fired power plant as 647.5 kg/s, the increasing capture level as 5% could capture additional 7.55kg/s of CO₂. It results in an annual captured amount over 0.23 Mt. In other words, at 90% capture level, such a solvent-based PCC would capture 3.86 Mt CO₂ each year. At 95% capture level, such a solvent-based PCC would capture 4.09 Mt CO₂ each year. An increase of 13.7% in reboiler duty represents a relatively small penalty when considered against the substantial reduction in residual CO₂ emissions achieved by moving from 90% to 95% capture. In the context of BECCS, where the objective is to maximise net negative emissions, reducing residual emissions from the treated flue gas is particularly important. Existing biomass-fired power plants and PCC infrastructure do not require complete reconstruction. This indicates that the higher capture level does not introduce impractical equipment requirements under the operating assumptions considered. Consequently, the additional regeneration energy associated with 95% capture can be regarded as acceptable for BECCS applications, provided that the objective is to minimise residual emissions and enhance negative emission performance.

6. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

Operating a PZ-based PCC process at a 95% capture level is technically feasible and does not incur a prohibitive energy penalty relative to the commonly used 90% benchmark. The additional captured CO₂ by setting at 95% capture level is about 653 tonnes per day, corresponding to an annual increase of more than 0.23 Mt (from 3.86 Mt CO₂ to 4.09 Mt CO₂). The reboiler duty rises to 4.07 GJ/tCO₂, corresponding to an increase of approximately 13.7% than 90% case. These results provide the necessary research foundation for the subsequent integration of the BECCS system with direct air capture technology. This study will first conduct further configurations, such as utilizing advanced flash stripper (AFS), intercooling system and rich-split process. This

study will also perform economic optimizations for the system. Optimal design and operation for high capture level biomass-fired power plant process using PZ can be achieved.

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