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Robust Simulation Platform of Biomass Gasification Process with Carbon Capture for Energy Vector Polygeneration

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Recent studies underscore the need for advanced technologies to limit global warming to below 2 °C and prevent irreversible climate change. This urgency is reflected in initiatives by the United Nations Framework Convention on Climate Change (UNFCCC) and the International Energy Agency (IEA). Carbon-negative solutions like the biomass gasification-carbon capture and storage (BECCS) hybrid systems are crucial, as BECCS is currently the only large-scale technology capable of removing CO_2 from the atmosphere. BECCS integrates sustainable biomass conversion via gasification combined heat and power (CHP) to generate electricity and heat, with post-combustion carbon capture (PCC) being one of the most mature CCS technologies available. In this work, a robust simulation platform of biomass gasification with PCC technology is developed using Aspen Plus software. The BECCS system is operated using palm kernel shells as a feedstock, while monoethanolamine with a concentration of 30 wt.% is used for the PCC plant. The performance evaluation of the BECCS system is conducted via sensitivity analysis. The simulation analysis shows that an increase in gasification temperature produces higher quality syngas with the optimal gasification temperature being 850 °C. Meanwhile, the optimal reboiler temperature obtained is 120.6 °C, indicating the optimal temperature for CO_2 desorption in the stripper. This study achieved a carbon removal rate of 99.94 %, and the highest power generated was observed to be 18 kW. The output from this robust simulation platform enables the minimization of overall emissions to below zero, offsetting emissions in other sectors where reductions are more challenging to achieve.

1. Introduction

Global climate change has become an increasingly pressing concern. A major contributor to this issue is the energy production sector, especially its reliance on fossil fuels. This sector accounts for a substantial portion of the increase in greenhouse gas (GHG) emissions, which are driving extreme climate changes worldwide (Martins et al., 2019). The most significant contributor to these emissions is the utilization of coal as an energy resource. In 2021, a major increase in CO_2 emissions was reported, with coal alone generating over 40 % of the total, contributing to 1.53×10^{10} t of global CO_2 emissions (IEA, 2021). The following years showed no improvement, as CO_2 emissions continued to increase, reaching 41.2 % (Friedlingstein et al., 2020). The rising global population has increased the demand for electricity, further exacerbating the issue (Haq et al., 2023). These scenarios have led to the exploration of alternative energy sources, with biomass emerging as a promising option. Biomass is widely available and poses minimal threat to the environment. This renewable energy source can be utilized for combustion and energy generation through the gasification process (Musharavati et al., 2022), offering a potential pathway to reduce reliance on fossil fuels and mitigate CO_2 emissions.

According to the International Energy Agency (IEA), integrating the bioenergy with carbon capture system (CCS) is a feasible strategy for reaching net zero and even negative CO_2 emissions (Ren et al., 2021). Bioenergy production is the process of producing electricity and heat from biomass, which is derived from agricultural

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leftovers and wastes (IEA, 2022). The adoption of BECCS in power production has the potential to significantly improve resource utilization efficiency. BECCS can also be viewed as a vector polygeneration system due to its capability to simultaneously produce multiple energy vectors. In this system, electricity is generated from biomass gasification, while heat is produced as a byproduct of power generation. Additionally, negative emissions are achieved through PCC plant.

Gustafsson et al. (2021) studied the reduction of energy penalties in BECCS plants, which has been a significant barrier to large-scale operations of the technology. Their research involved using hot potassium carbonate as the solvent in a CCS system for a biomass gasification combined heat and power (CHP) plant. Through thermodynamic analysis in Aspen Plus, they achieved an energy penalty of only 2 - 4 %. A similar CO_2 removal process was employed by Rabea et al. (2023), who used hot potassium carbonate for CO_2 absorption and stripping. Subramanian and Madejski (2023) concluded that net zero carbon emissions are achievable using syngas in a BECCS system, especially in a combined cycle configuration. They found that gas turbines running on 100 % syngas fuel generate more than 50 % exhaust gas, which can be captured by post-combustion CO_2 capture systems. Their study emphasized the importance of equipment power consumption, steam supply to the reboiler, and power consumption reduction in the design of BECCS systems. Only a limited number of studies highlight the interaction of BECCS plant operational variables. Thus, the present work performs a sensitivity analysis of an integrated plant by considering significant input-output variables: gasification and reboiler temperatures in relation to syngas output, reboiler duty and CO_2 captured. Optimal operating conditions for these input variables are evaluated to ensure feasible and efficient operation of the BECCS plant.

2. Methodology

2.1 Development of biomass gasification CHP system

This work used palm kernel shell (PKS) as the feedstock for the biomass gasification combine CHP system due to its wide availability and favourable physicochemical properties. With a calorific value of 15.63 MJ/kg, PKS outperforms other biomass sources such as rice husk and sugarcane bagasse, which have calorific values of only 12.30 MJ/kg and 13.51 MJ/kg (Awulu et al., 2023). PKS also has advantageous physicochemical properties, notably its low moisture content, which reduces energy consumption in the drying process and makes the process more efficient. The simulation flowsheet for PKS gasification with a CHP model was developed in Aspen Plus and adapted from the work of Kamaruzaman and Abdul Manaf (2023) where the Peng-Robinson Equation of State with Bronston-Mathias Modifications method is employed. The proximate and ultimate analysis for PKS, obtained through thermogravimetric analysis (TGA), serves as the initial biomass data for the model. The gasification operates at 750 °C and 1 bar, while the combustion chamber operates at 500 °C and 1 bar. The air stream fed to the gasifier consists of 71 % nitrogen and 21 % oxygen. The model was validated using the root mean square error (RSME), where the model has proved minimal error of not more than 2, as shown in Table 1.

Table 1: Comparison of results from literature data

Reference	Feedstock	Syngas composition (mol%)								RSME
		Experimental data				Present Model				
		H_2	CO	CO_2	CH_4	H_2	CO	CO_2	CH_4	
Maneerung et al. (2018)	Redwood pallet	14.86	17.34	9.90	3.72	14.73	16.94	10.54	0.0159	1.891
Ferreira et al. (2019)	Pine	18	19	12	2.9	18.93	19.62	11.15	0.0796	1.575
García et al. (2018)	Coffee-cut stems	19.53	16.32	13.77	3.42	19.96	18.92	11.83	0.881	2.071

2.2 Development of PCC system

In this study, a monoethanolamine (MEA)-based PCC system was developed using Aspen Plus software. The PCC model was adapted from the works of Ghiat et al. (2020) and Madeddu et al. (2019), where a rate-based model using the Electrolyte NRTL property model with the Redlich-Kwong equation of state is employed. The present model excluded the MEA make-up tank and water wash for process simplification. Furthermore, the present work assumes a constant process operation for the make-up the tank, and water where the variation is focused only on the MEA solve flow rate. To ensure the reliability of the developed PCC model, the model was validated by comparing it with data from Ghiat et al. (2020) and Madeddu et al. (2019). Tables 2 and 3 present a comparative analysis between the literature model and the model developed in this study. The RMSE calculations between the literature data and the proposed model yielded values less than 1 for most parameters. The exception is the CO_2 capture comparison between this model and that of Ghiat et al. (2020). This discrepancy arises from methodological differences: Ghiat et al. used a fixed CO_2 capture value in their rate-based modeling approach, while the current study employed a fixed solvent flowrate. Notwithstanding this difference, the simulation results are considered credible and reliable due to their close alignment with the literature data across other parameters.

Table 2: Comparison of results from literature data

Parameter	Literature Data (Madeddu et al., 2019)	This Model	RSME
CO_2 Removal (%)	99.63	99.94	0.306
Loading Out	0.457	0.454	0.003

Table 3: Comparison of results from literature data

Parameter	Literature Data (Ghiat et al., 2020)	This Model	RSME
CO_2 Removal (%)	80	99.94	19.936
Negative Emission (kg/kWh of CO_2)	-0.310	-0.003	0.307

2.3 Integration of PKS gasification with CHP system and PCC plant (BECCS)

The PKS gasification with the CHP model is integrated with the PCC model to form a BECCS model in Aspen Plus software, as illustrated in Figure 1. The exhaust gas from the gas turbine of the gasification model is cooled down. Then, the gas is flowed to the inlet of the absorber column of the PCC model. It is crucial to cool the exhaust gas before entering the absorber to reduce the water content in the gas stream as this will induce solvent degradation. The CO_2 from the exhaust gas is directly captured ensuring zero carbon emission from the biomass gasification system.

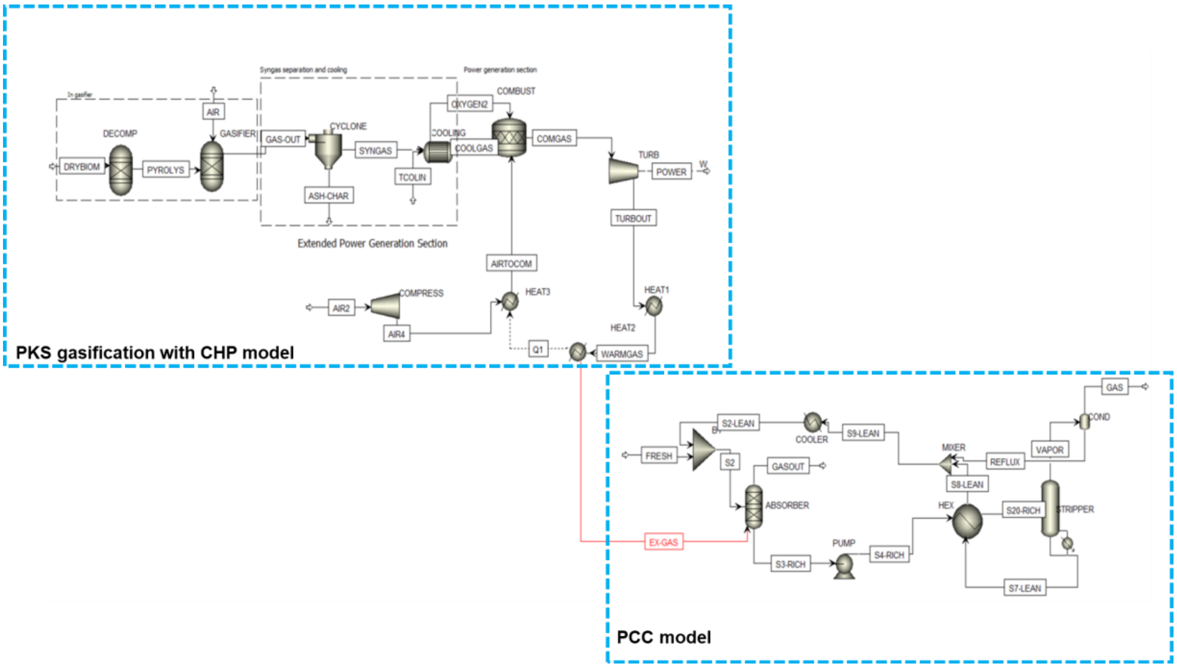

Figure 1: BECCS flowsheet model

3. Result and Discussion

3.1 Effect of Gasification Temperature on the Syngas Composition

In the PKS gasification process, the most dominant effect towards the syngas output can be seen when the gasification temperature is varied. The decomposition of biomass to syngas takes place at greater temperatures, leading to more syngas generation. Higher temperature may promote reactions such as water-gas shift, Boudouard, steam methane reforming, and tar cracking. These conditions align with Le Chatelier's principle, which states that high temperatures favour reactants in endothermic reactions and products in exothermic reactions. In this analysis, the gasification temperature was varied from 450 °C to 850 °C, while other parameters remained constant. The syngas output was studied based on the mole fraction of the components produced, such as CO_2, H_2, CO, and CH_4, as shown in Figure 2. As the temperature increased, the compositions of CO_2 and CH_4 decreased, while those of H_2 and CO showed an upward trend, peaking at 623 °C. This trend aligns with observations from the study conducted Lan et al. (2018). According to gasification principles, H_2 and CO serve as key indicators for determining the ideal gasification temperature. The crossover point of these two components on the graph is considered the optimal gasification temperature for PKS, which was found to be 850 °C. At this temperature, the system achieved the highest power output of 18 kW, as illustrated in Figure 3. Notably, CO_2 production is also at its lowest at this temperature, simultaneously minimizing CO_2 emissions and enhancing the process's efficiency.

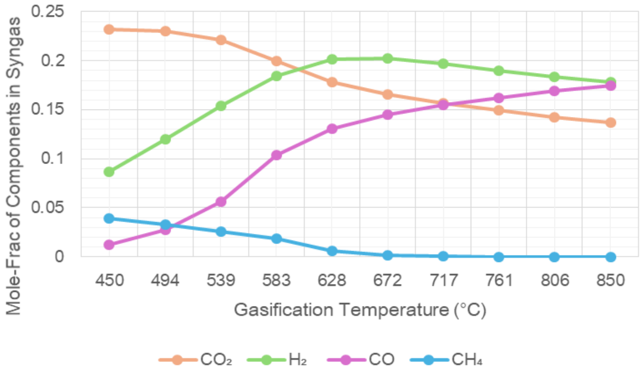

Figure 2: Correlation between gasification temperature and syngas component distribution

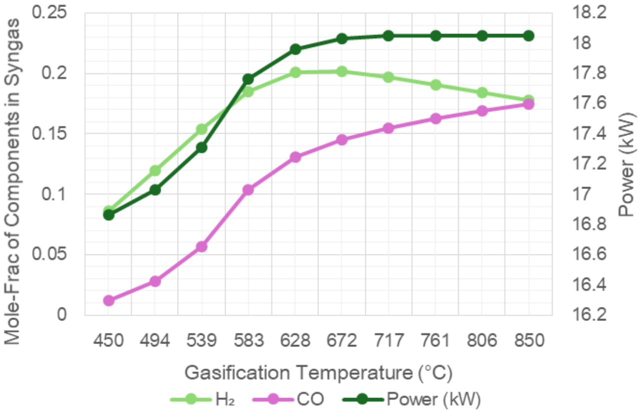

Figure 3: Optimal gasification temperature for biomass gasification with CHP system

3.2 Effect of Reboiler Temperature on CO_2 Flowrate in Absorber and Stripper Columns

The temperature of the reboiler and condenser at the stripper plays a crucial role in the desorption of CO_2 from the solvent. Raising the reboiler temperature can improve the absorber's reversibility, making it easier to remove CO_2 and reduce the reboiler duty (Shukla et al., 2023). To study the effects on the mass flow of CO_2 in the produced gas of both the stripper and absorber, the reboiler temperature was varied from 120 °C to 125 °C as illustrated in Figure 4. An increase in the reboiler temperature produced a higher CO_2 concentration of produced gas in the stripper but showed a decrease in the CO_2 of the produced gas in the absorber. This is because higher reboiler temperatures increase the reversibility of the processes in the absorber, making it simpler to extract CO_2 from the rich solvent. While a higher reboiler temperature enhances CO_2 desorption in the stripper. This is because increasing the reboiler temperature reduces the driving force for CO_2 absorption in the absorber as the lean solvent loading is also lowered (Dey et al., 2018). The crossover between the two points in Figure 5 indicates the optimal reboiler temperature to be 120.6 °C at a capture level and reboiler duty of 99.99 % and 80 kW. This value is acceptable as the degradation of amine is induced beyond 122 °C, which causes a loss of solvent (Adu et al., 2020). At this condition, MEA possessed acceptable thermal stability and represented a good balance between effective CO_2 desorption and energy consumption.

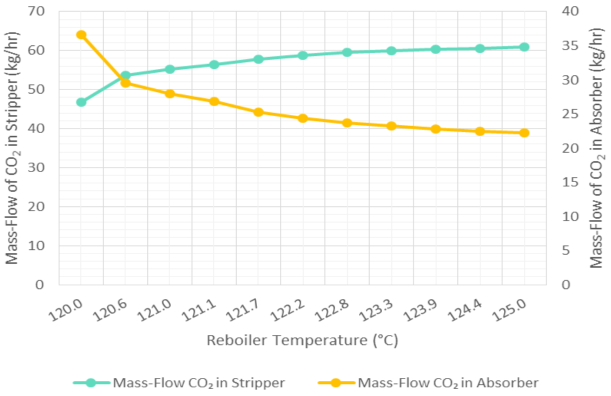

Figure 4: Correlation between reboiler temperature on CO_2 flowrate in absorber and stripper columns

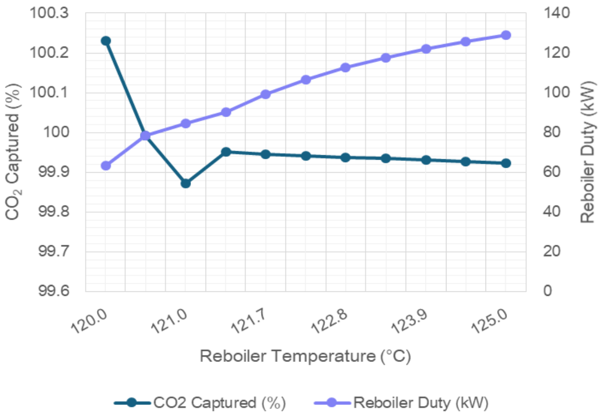

Figure 5: Optimal reboiler temperature for BECCS model

4. Conclusion

This paper presents a robust simulation platform of clean energy technology via biomass gasification with a carbon capture system to achieve carbon-negative emissions. The present work achieved a carbon capture removal rate of 99.94 %, with an observed power generation of 18 kW, based on an inlet feed of 100 kg/hr of PKS. The simulation analysis demonstrated that increasing gasification temperature produced higher quality syngas, with desirable increases in H_2 and CO formation, while CO_2 and CH_4 formation declined. The optimal gasification temperature was identified as 850 °C, indicated by the crossover between the H_2 and CO trends. The optimal reboiler temperature was found to be 120.6 °C. In addition, a negative carbon emission of -0.00295 kg/kWh of CO_2 is obtained through the simulation analysis, which makes evident the potentiality of BECCS technology as an alternative to clean energy. This preliminary analysis shows that BECCS in power generation can significantly contribute to net zero/negative carbon emissions. The proposed simulation platform is capable of minimizing overall emissions to below zero, potentially offsetting emissions in sectors where reductions are more challenging. Future studies can be extended by utilizing different types of biomass feedstock and solvents in large-scale setups. Further consideration of life cycle assessments on the environmental impact of BECCS may bolster the credibility of this proposed negative emission technology. Finally, governments should consider providing incentives to promote this new technology, in addition to raising public awareness about the clear benefits of BECCS systems for long-term sustainability.

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