

Sensitivity analysis of small scale biomass gasification-based CHP system: A way forward for sustainable urban waste to energy technology

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Abstract. A biomass gasification-based combined heat power (CHP) system emerges as a potential sustainable urban waste-to-energy (WtE) technology that can offer solutions to the excessive anthropogenic CO₂ emissions and the escalation of energy demand as well as to the incremental of domestic and agriculture wastes. In this work, a steady state flowsheet model of 25 kW APL power pallet is developed by Aspen Plus software. The developed power pallet model integrates physical and chemical processes which involves pyrolysis, combustion, and gasification processes. The developed gasification model is validated with experimental data using biomass woodchip as a feedstock. This study focuses on the gasification of biomass to produce syngas (mainly H₂ and CO) which subsequently converts to electric power. As an initial study towards large scale WtE plant, a detailed parameter sensitivity analysis is performed by analysing variables effects on syngas production subjected to the manipulation of gasification temperature, pressure and air-to-biomass ratio. The results show that the elevation of air-to-biomass ratio and gasification temperature contribute to the high conversion of CO subsequently enhance the potential of electrical power load. Moreover, power pallet exhibits optimal operation at 3.9 of air-to-biomass ratio with gasification temperature approximately at 1200 K. The initial results obtained in this study are valuable in determining the feasibility of biomass gasification-based CHP system as a sustainable and robust WtE technology.

1. Introduction

Malaysia is one of the highest energy-related CO₂ emitters among South-East Asian countries, mainly attributed to the country's emissions from the power generation sector. It is forecasted that energy demand will increase to triple towards 2040 due to the rapid urbanization consequently jeopardizing the national environmental sustainability and energy security. This scenario correlates to the increment of municipal solid waste (MSW) which resulted from the steep growth of population and industrialization. Additionally, Malaysia also produces enormous abundance of agriculture biomass/forest residues whereas both (MWS and agriculture biomass/forest residues) can be utilized as a renewable/alternative energy source. Based on the forecast population, Malaysia expected to generate more than 5,000 metric tonnes of domestic waste per day with the major contribution comes from the urban areas such as Selangor, Kuala Lumpur and Pulau Pinang as depicted in figure 1(1). This situation presents a significant waste management challenge especially to those metropolitan cities. Whereas, together with inadequate



infrastructure and technology deployment, limited budget in managing the waste and land scarcity has made urban waste management a priority area for the Malaysian Government (2).

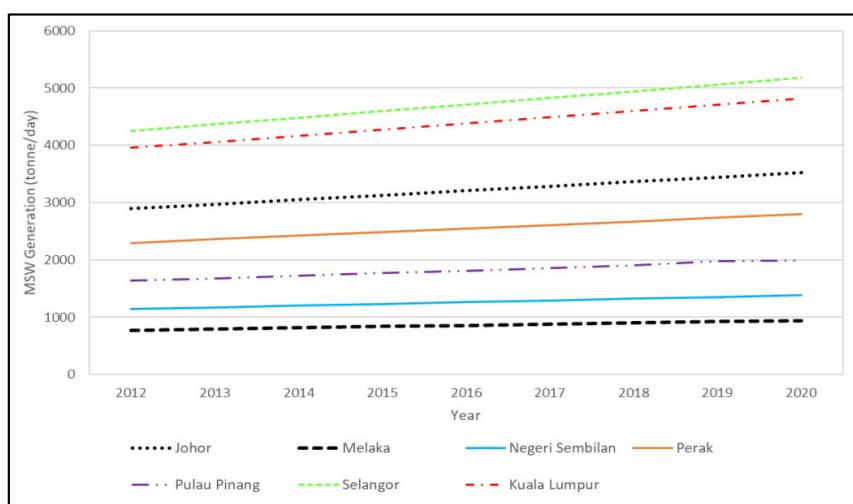


Figure 1. MSW generation in Malaysia by states, from 2012-2020.

The Waste to Energy (WtE) technologies have moderately been discussed and explored since past few decades. However, a recent impact on the global warming and climate change has enforced international organization to move forward to the alternative energy resource, such as WtE. Biomass gasification system integrated with combined heat power (CHP) system emerges as a feasible solution to overcome those challenges. A biomass gasification operates by producing the synthesis gas/syngas (mainly H_2 and CO) which subsequently be converted to electric power through the CHP system. However, transient behavioural of this integrated system (gasification-based CHP system) inflicts operational complexity due to the inconsistencies in feedstock properties for instance calorific value, moisture content and volatile matter. Whereby, these variations may affect the operation and performance of gasification-based CHP system for instance, syngas production, gasification temperature and thermal efficiency. Thus, application of process simulation model is of significant important to identify actual behaviour and performance of the process in computational way without require repetitive experiments (increase experimental and operational cost).

According to Dalai, Batta (3), the optimum temperature for better H_2 and CO selectivity was determined at $725^\circ C$. The calorific value of product gas produced at lower gasification temperature is significantly higher than that of gas produced at higher process temperature. Also, the composition of feedstock plays an important role in distribution of products gas. The feedstock with more C and H content is found to produce more amounts of CO and H_2 under similar experimental conditions. Niu, Huang (4) reported the effects of operating parameters on syngas composition and gasifier efficiency, including gasification temperature, equivalence ratio (ER), oxygen percentage (OP), MSW moisture content, and steam/MSW ratio. It was indicated that higher temperature favours the production of H_2 and CO and leads to higher gasification efficiency. Whereas, increasing the ER is able to improve the

CO yield. Table 1 tabulates the summarization of operating conditions and performances of gasification units under various types of modelling approach. This collection of literature review is beneficial to understand the sensitivity and significant parameters impacted the gasification operation.

2. Methodology

A steady state flowsheet model of biomass gasification system is developed based on the actual operation of 25 kW power pallet consisted of a downdraft gasifier integrated with the combined heat power (CHP) system as illustrated in Figure 2. The gasification exposed woodchip to the procedures of drying, pyrolysis, combustion, cracking, and reduction. Separation tar gases into CO, H, and other light gases by introduction to high temperatures was known as producer gas. Based on figure 2, the PYROLYS and PRESCORR blocks were used to simulate the biomass pyrolysis process. The COMBUST block was used to model the volatile combustion process. The GASIFIER block is for the char gasification process. To simplify the simulated model, only downdraft gasifier is being modelled while the performance of CHP system is predicted by the amount of syngas production. In this study, woodchip is used as a feedstock while the averaged ultimate and proximate analyses were calculated and analysed as stated in Table 2. The composition of the woodchip is analysed by using Carbon, Hydrogen, Nitrogen (CHN) analysis.

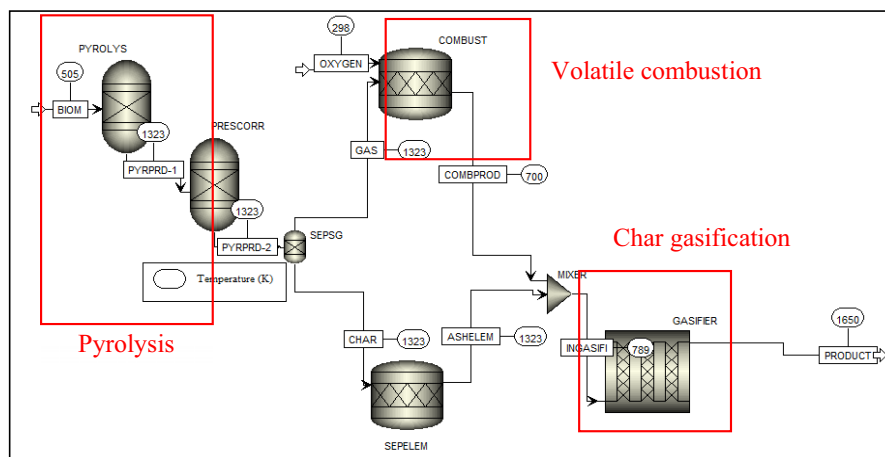


Figure 2. Flowsheet model of downdraft gasifier system.

Table 2. Experimental ultimate and proximate analysis of the woodchip.

Ultimate and proximate	This work
Moisture content (%)	< 4

Carbon (%)	45
Hydrogen (%)	5
Nitrogen (%)	< 0.1
Oxygen and Sulfur (%)	35.3

Table 1. Summary of operating conditions and performances of wastes gasification units.

References	Waste type	Type of modelling APM or MM	Type of reactor FB, BFB, CFB or ABG	Operating condition					
				Moisture (%)	Oxidizing agent	Temperature (oC)	H ₂ (%)	CO (%)	LHV (MJ/Nm ³)
Niu, Huang (4)	MSW	APM	BFB	30.0	Air	800	12.0	25.0	4.8
Niu, Huang (4)	MSW	APM	BFB	50.0	Air	800	8.5	26.0	4.2
Ribeiro, Soares (5)	RDF	APM	-	-	-	750, 850	-	-	-
Shehzad, Bashir (6)	MSW	APM	CFB	51.7	O ₂	900	28.0	25.0	N.A.
Vounatsos, Atsonios (7)	RDF	APM	AB	-	-	850-900	-	-	-
Haydary (8)	RDF	APM	-	10	Air, Steam, O ₂	676	18.8	19.7	4.6-10
Násner, Lora (9)	RDF	APM	FB	30	Air	650-750	-	-	5.8
Niu, Huang (4)	MSW	APM	BFB	10.0	Air	800	16.0	24.0	5.4
Niu, Huang (4)	MSW	APM	BFB	30.0	Air	800	12.0	25.0	4.8
Niu, Huang (4)	MSW	APM	BFB	50.0	Air	800	8.5	26.0	4.2

N.A.: is not available, APM: Aspen Plus Modelling, MM: Mathematical Modelling, FB: Fixed Bed, BFB: Bubbling Fluidized Bed, CFB: Circulating Fluidized Bed, ABG: Air Blown Gasifier

3. Result and Discussion

3.1 Sensitivity analysis

The biomass gasification using air as gasification agent is carried out. Aspen Plus modelling as illustrated in Figure 3-4 showed different behavioural characteristic with respect to pressure and temperature difference. Figure 3 displayed the combustible gases inside the product stream. It showed that during gasification, the differences in pressure produced different mass fraction of CO and H₂. The lower the pressure, the higher the mass fraction of CO produced. While the higher the pressure, the lower the mass fraction of CO produced. This showed that production of CO is more favourable in a lower pressure condition than in a higher pressure condition. The result was similar to the study conducted by (10) where they indicated that the best condition to obtain the maximum yield of CO formation was at high reaction temperature and lower operating pressure (10).

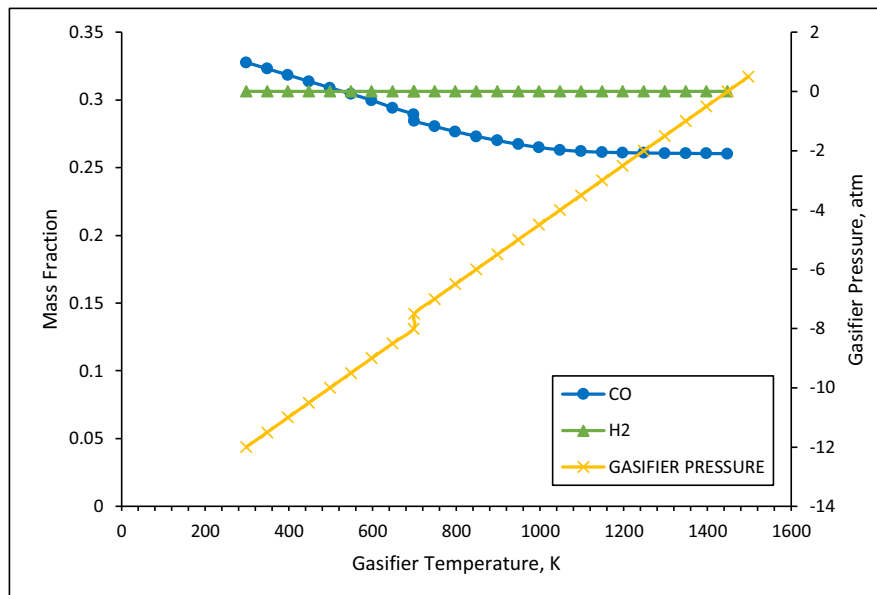


Figure 3. Effect of pressure changes to the syngas production.

Figure 4 displayed the major combustible components in syngas such as CO, CO₂, and H₂ in the product stream. At low temperature, both unburnt carbon and CH₄ are present in syngas. As the temperature increases, carbon is converted into CO (Boudouard reaction). While CH₄ is converted into H₂ by reverse Methanation reaction. This resulted in the production of H₂ and CO. Production of CO decrease gradually with the temperature and remain constant when reaching 1000 K.

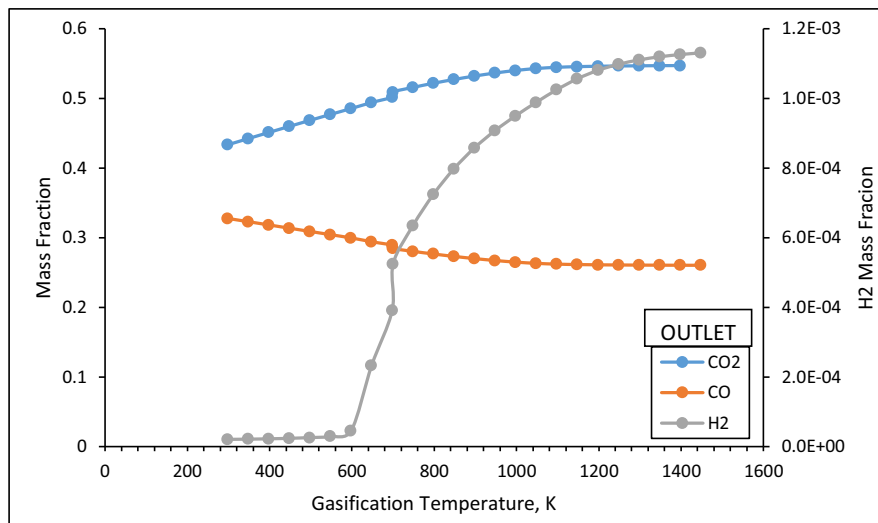


Figure 4. Effect of temperature changes to the syngas production.

3.2 Optimal operation of the gasification process

Figure 5 depicts the behaviour of the biomass gasification process at different air to biomass ratio. It is indicated that the optimal condition of biomass gasification system was exhibited at $m_{(air)}/m_{(RDF)} = 3.9$ with 27% conversion of CO at 1200 K. Similar trend was observed in the study conducted by (11). Whereas, their study predicted that at 850 K, CO conversion was at 50% at $m_{(air)}/m_{(RDF)} = 3.2$ (11).

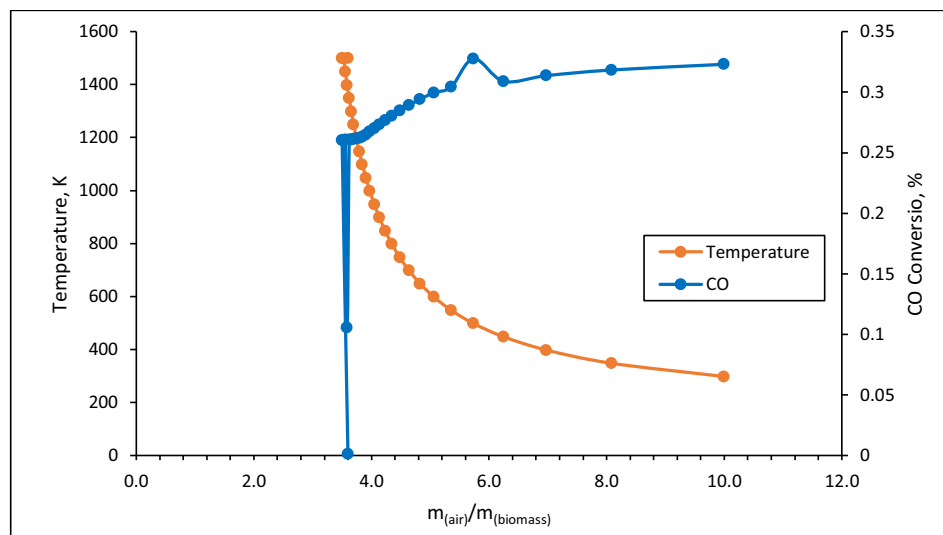


Figure 5. Conversion, and reactor temperature at different $m_{(air)}/m_{(biomass)}$ ratio using air as gasification agent.

4. Conclusion

This study performs sensitivity analysis of 25 kW APL power pallet consisted of downdraft gasifier by using Aspen simulation software. The biomass (woodchip) gasification system encompasses of drying, pyrolysis, combustion, cracking, and reduction procedures. The results show that the production of

syngas is influenced by the gasification temperature and pressure. Whereby, the increment of syngas flowrate represents the possible power load that can be generated. Moreover, power pellet exhibits optimal operation at 3.9 of air-to-biomass ratio with gasification temperature approximately at 1200 K with 27% conversion of CO.

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