Simulation of Palm Kernel Shell Gasification for Small Scale Power Generation Using Aspen Plus Software

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Abstract. In this study, a simulation flowsheet model of gasification process for small-scale power generation was developed in Aspen plus software in accordance with the actual 20-kW power pallet unit manufactured by All Power Labs Power Pallet. The flowsheet model is capable to determine the syngas composition and amount of power load generated from the internal combustion engine. Biomass feedstock used in the model was palm kernel shell as it possesses a favourable physiochemical property and easy to obtain. Proximate and ultimate analyses data were used as the basis for the flowsheet model to reflect the physical property of palm kernel shell as a non-conventional component. The gasification of palm kernel shell was simulated into four main processes which are drying, pyrolysis, combustion and reduction by using two R-Stoic models and individual R-yield and R-Plug model with specification of chemical reactions, dimensions and operating conditions of the process. The results obtained from the model were validated with experimental data of palm kernel shell gasification process at a similar operating temperature acquired from previous research studies. Several parameters such as gasification temperature, air preheating and pyrolysis temperature were studied under specified value subjected to the amount of power load generated. It can be seen that the gasification temperature, air preheating temperature and pyrolysis temperature were found to have a directly proportional trend on power load based on their respective temperature range. Furthermore, optimal power load (≈ 20 kW) can be generated at pyrolysis temperature of 460 ℃ with gasification and intake air temperature of 1200 ℃ and 550 ℃ respectively. This work is of significance for preliminary operational and plant design benchmark if the government is considering a large-scale development of biomass power generation.

1. Introduction
Malaysia has shown an increasing projection of electricity consumption by 2030. As Malaysia’s economy and population develops, the demand of electricity has increased reaching 12,606 kilo tonnes of oil equivalent in 2017. According to the statistical data from Malaysia Energy Information Hub (MEIH), electricity consumption in Malaysia shows an increasing trend every year, with a drastic increment of 7,344 kilo tonnes of oil equivalent from the year 2000 to 2017. Due to this, World Energy Markets Observatory has forecasted that electricity consumption in Malaysia will maintain the same trend with a 4.8% increment by the end of 2030 [1]. However, it is afraid that this consumption pattern will cause many environmental issues, since Malaysia is heavily dependent on limited fossil fuels.
combustion as a main energy contributor. Apart from that, due to economic and population growth, these factors contribute to waste generation in a large amount associated with numerous environmental impacts. According to the statistical data from The World Bank, Asia contributes about 802 million tonnes of solid waste per year in 2018 [3]. Based on this number, Malaysia contributes about 38,000 tonnes of solid waste per day [4]. Being a major agricultural commodity producer in Asia, Malaysia produces approximately 168 million tonnes of biomass annually. In 2018, Malaysia Palm Oil Board reported that there are 451 palm oil mills existed in Malaysia, which produce approximately 84.74 million tonnes of biomass including palm kernel shells (PKS), fibres, and other residues. Unfortunately, these precious resources that has electricity generation potential and value-added product are being discarded without proper treatment. At present, gasification process emerges as a sustainable power generation system as it emitted low level of pollutant. Despite its advantages in maintaining environmental sustainability, gasification process encounters several issues that limits its efficiency and the quality of syngas, since this complex process involves large chemical reaction in different pathway. Therefore, a comprehensive flowsheet model is required to understand the behaviour and reaction of PKS gasification process to generate small-scale power generation before moving towards a commercial one.

2. Literature review
Prior studies have identified that a successful gasification system is influenced by various factors. Temperature is the one of the key factors that can contribute to an effective gasification. According to Basu [5], in order to obtain syngas from the gasification process, it is necessary to react the carbonaceous material at high temperature with the presence of gasifying agents, as the combustion process is likely to occur at higher temperature. Lan et al. [6] found that as the temperature of the gasification increased, the composition of H2 and CH4 also showed an increasing trend. On the other hand, Olaleye et al., [7] studied the prediction of pyrolysis temperature subjected to variation of gasification temperature between 300 ℃ to 800 ℃. They found that there were no significant changes on the production of char, oil and syngas at the pyrolysis temperature between 300 ℃ to 600 ℃. Additionally, few studies have been done related to the effect of air preheating towards the performance of biomass gasifier [8,9]. Their studies exhibited that preheating of air in gasifier reactor manage to help in the production of a better quality of syngas. It can be observed that most of the existing works have only discussed related to the effect of gasification temperature, air preheating temperature and pyrolysis temperature towards the syngas production. However, only scare studies explored those factors against the power load generation. Thus, this study fills in the existing research gap by predicting the profile of these three variables/factors in order to generate optimum power generation via small scale power system.

3. Methodology
A simulation flowsheet model of PKS gasification with combined heat and power (CHP) system was developed using Aspen Plus software based on the actual 20-kW (± 2 kW) power pallet unit manufactured by All Power Labs [10]. The flowsheet model reflects the power pallet in terms of processes, chemical reactions, and operating conditions. Proximate and ultimate analyses data of PKS from Waluyo et al., [11] was used as the physical property of PKS. The gasification process was illustrated via four processes which includes drying, pyrolysis, combustion, and reduction process by using R-Stoic, R-yield, and R-Plug models. While, CHP system in the power pallet unit encompassed of gas filtration, gas cooling, combustion of syngas in the internal combustion engine (ICE) and power generation process inside the generator. This system was illustrated by using SSplit, HeatX, Rstoic and Compr models. This simulation flowsheet was developed by assuming that a steady-state flow is considered inside the gasifier.
4. Result and discussion

4.1 Flowsheet Model of PKS Gasification with CHP System

Flowsheet model of PKS gasification process was adapted and improved from Rasid et al. [12] while, this present work develops a new CHP model (power generation process) and integrated it with a previously developed gasification model as illustrated in Figure 1. The CHP flowsheet model developed in this work was referred to a similar study conducted by [13]. The performance of PKS gasification with CHP was evaluated based on the parametric studies to understand the behavioural performance of the developed small-scale power plant flowsheet model. This analysis is done based on the influence of gasification temperature, air preheating temperature and pyrolysis temperature towards power plant load generation. A simple validation process was conducted to support the reliability of the developed flowsheet model based on literature data available in [14-16] (not shown in this paper).

![Figure 1. Simulation flowsheet of PKS gasification with CHP system.](image)

4.2 Parametric studies

4.2.1. Effect of Gasification Temperature on Power Load.

Flowsheet model of PKS gasification with CHP system shows different behavior toward different ranges of gasification temperature. Based on the developed flowsheet model, the effect of gasification temperature towards the amount of power load was studied based on the temperature ranging from 600 °C to 1000 °C. In this study, 600 °C is considered as the minimum temperature of the gasification process since high reactivity of carbon to reduce water vapor and CO₂ can only be achieved at a temperature above 600 °C. The behavior and trend for the amount of power load is illustrated in Figure 2. Based on the figure, it is observed that the amount of power load generated is increasing along with the increment of gasification temperature. Due to this, it can be concluded that power load is linearly proportional to gasification temperature. Similar trends are also available in the research study by Maneerung et al. [17] on gasification of redwood pellet. This trend is formed due to the increasing value of H₂ yield from the gasification process that acts as a fuel for electricity generation. Therefore, a high temperature of gasifier is preferable in order to obtain high power load.
4.2.2. Effect of Air Preheating on Power Load.

The conditions of air preheating for combustion process also play a crucial role in gasification of PKS as well as to obtain high power load from the internal combustion engine. The influence of air preheating was studied towards the amount of power load where the condition is represented by the temperature of air ranging from 25 °C to 700 °C. The intake air temperature of 25 °C in this study is considered as the initial temperature of air without preheating. The results of the study are illustrated in Figure 3. It is proved that the temperature of air preheating (intake air) is directly proportional to the amount of power load. This trend is in good agreement with the results obtained by Doherty et al., [9] where H₂ and CO composition were found to increase as intake air temperature increases. This trend is obtained due to the sensible heat of air that causes the increment in gasification temperature resulting in more combustible gases for electricity generation. It was observed that the intake air should be preheated up to 600 °C in order to obtain high power load.

![Figure 3. Changes in intake air temperature versus the amount of power load.](image-url)
4.2.3. Effect of Pyrolysis Temperature on Power Load.
Based on the developed flowsheet model, the effect of pyrolysis temperature was analysed towards the amount of power load using the temperature range of 400 °C to 500 °C. The results of the study are represented in Figure 4. According to the figure, it can be observed that pyrolysis temperature is proportional to the amount of power load. Along increasing value of pyrolysis temperature, the amount of power generated from the internal combustion engine shows an increasing trend from 20.86 kW to 20.96 kW. This trend is believed due to higher conversion of pyrolysis reaction at high temperature resulting in more fuel gases are being produced. Therefore, it can be concluded that high temperature of pyrolysis is preferable in order to obtain high power load.

4.3 Optimal Operation of PKS Gasification with CHP System.
In practical, the actual process of 20-kW power pallet is in batch process. Figure 5 shows the optimal power load that can be generated from PKS gasification with CHP system according to the actual process of power pallet used in the study. According to the figure, at preheating air and pyrolysis temperatures of 460 °C, the internal combustion engine is capable to produce power load up to approximately 20.75 kW. Besides that, the graph also shows that the gasification temperature is independent with preheating air and pyrolysis temperatures. This is because gasification temperature reflects the actual batch process of power pallet where PKS will undergo pyrolysis and gasification process separately at different operating temperature. If pyrolysis temperature can be maintained throughout the process, the maximum power load that can be produced from internal combustion engine is at approximately 20.9 kW which is achievable at gasification temperature of 1000 °C. Therefore, it can be concluded that the optimal operation of PKS gasification with CHP system can be obtained at preheating air and pyrolysis temperature of 460 °C and gasification temperature of 1000 °C.

![Figure 4](image_url)  
**Figure 4.** Changes in pyrolysis temperature versus the amount of power load
Since pyrolysis temperature cannot be controlled in the actual operation of power pallet, two possible optimal operations of PKS gasification with CHP system are proposed in this study to support the actual performance of power pallet. Figure 6 illustrates the relationship of pyrolysis, gasification, and intake air (air preheating) temperature that reflects its trend toward the amount of power load. In order to determine the optimal operation of PKS gasification with CHP system, the interception point of those variables mentioned before was analyzed. Based on the figure, it was indicated that the optimal operation of PKS gasification process equipped with small-scale power generation unit was exhibited at pyrolysis temperature of 460 °C with gasification and intake air temperature of 1200 °C and 550 °C, respectively. These results show the actual operation of power pallet where the pyrolysis temperature cannot be controlled.

**Figure 5.** Gasification, intake air and pyrolysis temperature versus the amount of power load

**Figure 6.** Gasification and intake air temperature at different pyrolysis temperature
Based on both parametric and optimal analyses, the PKS gasification with CHP system is capable to generate maximum power load that has been customised for the actual power pallet. Even though the trend and behaviour of the process variable is smaller in term of value, however, the results of this study are useful for preliminary study and further application on large-scale gasification process for power generation. This is because the developed flowsheet model can be easily scale up according to the specified internal combustion engine capacity. Furthermore, the findings are also important to be used as reference in understanding the behaviour and performance of gasification process for power generation in large-scale application.

5. Conclusion
Gasification, preheating air (air intake) and pyrolysis temperature are directly proportional to the power load. By increasing the temperature of all parameters, it resulted in the increased of power load with intake air reaching the highest at 600 °C. The optimal operation of PKS gasification with CHP system can be obtained at pyrolysis temperature of 460 °C with gasification and intake air temperature of 1200 °C and 550°C, respectively.

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