Gasification of empty fruit bunch with carbon dioxide in an entrained flow gasifier for syngas production

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Abstract. The main objectives of this work are to study the gasification of EFB in an atmospheric entrained flow gasifier, using carbon dioxide (CO₂) as its gasifying agent and to determine the optimum gasification operating conditions, which includes temperature and the oxidant to fuel (OTF) ratio. These were evaluated in terms of important gasification parameters such as the concentration of hydrogen (H₂) and carbon monoxide (CO) produced the syngas ratio H₂/CO and carbon conversion. The gasification reactions take place in the presence of CO₂ at very high reaction rate because of the high operating temperature (700°C - 900°C). The use of CO₂ as the oxidant for gasification process can improve the composition of syngas produced as in the Boudouard reaction. Rise of reaction temperature which is 900°C will increase the concentration of both H₂ & CO by up to 81% and 30% respectively, though their production were decreased after the OTF ratio of 0.6 for temperature 700°C & 800°C and OTF ratio 0.8 for temperature 750°C. The operating temperature must be higher than 850°C to ensure the Boudouard reaction become the more prominent reaction for the biomass gasification. The syngas ratio obtained was in the range of ≈ 0.6 – 2.4 which is sufficient for liquid fuel synthesis. For the carbon conversion, the highest fuel conversion recorded at temperature 850°C for all OTF ratios. As the OTF ratio increases, it was found that there was an increase in the formation of CO and H₂. This suggests that to achieve higher carbon conversion, high operating temperature and OTF ratio are preferable. This study provides information on the optimum operating conditions for the gasification of biomass, especially the EFB, hence may upsurge the utilization of biomass waste as an energy source.

1. Introduction

Nowadays, fossil-based fuels are the main energy source. However, renewable and clean energy sources are now under focus as the alternative and the more sustainable supplies of energy in the future due to energy crisis and environmental issues that has been plaguing the usage of the conventional fuels. There is a potential in the greenhouse gas emissions reduction by fossil fuels burning through renewable resources [1-3].

One of the major renewable energy resources which can produce hydrogen (H₂) as a clean, sustainable, environmental-friendly energy sources is biomass. Biomass is the top four among the primary energy sources such as coal, oil and natural gas and currently caters for about 14% of the world’s total energy consumption [4]. The use of biomass as renewable energy is important to alleviate global warming [5]. Biomass has high potential in produce zero net carbon dioxide (CO₂) emissions [6-7]. It can be converted into gas or liquid fuels through bio-chemical or thermochemical processes.
Oil palm is one of the most intensive producers of biomass. Oil palm mill generates three main types of waste which are solid waste (mesocarp fruit fibers (MF), palm kernel shell (PKS), EFB), liquid waste (palm oil mill effluent (POME)) and air waste (smoke from boiler and incinerators [8-10]. In Malaysia, the oil palm solid waste including EFB, PKS and fibres are cheap and abandoned materials produced during palm oil milling process. Approximately 0.07 tons PKS and 0.2 tons EFB solid waste are produced for every ton of oil palm fruit bunch during milling [11]. In palm oil mill, about 90% of the total biomass is considered as waste or 50-70 tonnes biomass residue from each hectares of production area while the other 10% constitutes to the extracted palm oil. These wastes have high fibre content and usually used as fuel in mill boilers. High moisture content of EFB cause it cannot be burn directly. Therefore, EFB usually dumped in plantation [8]. Table 1 show the quantity of major Oil Palm Wastes (OPWs) generated from Crude Palm Oil (CPO) in 2014 [9].

| Oil Palm Waste (OPW) | % OPW | OPW generated(tons) |
|----------------------|-------|---------------------|
| Empty Fruit Bunches (EFB) | 22.00 | 15,472,600          |
| Mesocarp Fibre (MCF) | 13.50 | 9,494,550           |
| Palm Kernel Shell (PKS) | 11.50 | 8,087,950           |

Malaysia was the largest oil palm producer for last few decades. But since 2007, Indonesia overtook Malaysia and become the world largest producer of oil palm. This is due to high availability of oil palm plantation area and increased in cultivation of oil palm in high pace [12]. For oils and fats market in global demand, palm oil is now the most important tropical vegetable oils as measured by either production or international trade [13]. In the period 1995-2010 palm oil production is more than tripled to 46.7 million tonnes, mainly produced by two major producing countries, Indonesia (47%) and Malaysia (38%) [14]. Crude palm oil production is reaching 52.31 million tons per year globally in 2012 and Southeast Asia is the main contributor, with Indonesia accounting for 48.94%, Malaysia 36.19%, and Thailand 3.10% [15]. Indonesia and Malaysia are the two major producers of palm oil in the world, contributed 19,500 MT and 30,100 MT respectively in 2014 [16]. Figure 1 shows Certified Sustainable Palm Oil (CSPO) production capacity for 2016.

![Figure 1. CSPO production capacity as for September 2016](image)

For Southeast Asian region based on the certified sustainable palm oil as September 2016, Indonesia and Malaysia produced 6.7 and 3.6 million tonnes respectively while Thailand produced 31,811 tonnes [17].
Palm oil contributes for about 5% of the world’s bio-diesel production. It has increased significantly due to increasing global demand with major importers being India, China and the European Union [18].

1.1. Biomass Gasification

Gasification is a clean technology that converts different carbonaceous feed stocks such as natural gas, coal, petroleum, coke, biomass and municipal solid wastes in a limited supply of air to gaseous products or called as synthesis gas such as H₂, carbon monoxide (CO), CO₂, water (H₂O) as well as gaseous hydrocarbons at high temperatures [19-22]. This process is one of the promising technologies that have been widely studied to exploit energy using several kind of feedstock, as coal, biomass or mixtures [23]. This process is one of the few technologies that can potentially produce carbon neutral energy with pollution-free power and also change the agricultural gas into energy [24].

Biomass and coal are considered as potential feedstock’s which supply syngas though gasification for the synthesis of liquid fuels. This is due to depletion of natural gas resources which increased the necessity for reducing the consumption of natural gas [25]. However, in comparison with coal, biomass may be able to produce cleaner syngas due to its lower sulfur contents and neutral carbon footprint [26, 27]. Biomass contains more oxygen and nitrogen in its elements and has the tendency to produce tar while coal contains more ash and sulfur. Generally, the O₂ and fixed carbon content of biomass are 45 wt. % and 20-25 wt. % respectively while for coal are 2-20 wt.% and 50-85wt.%. The [H₂] / [CO] ratio for biomass is higher than coal which is in the range of between 1.7– 2.1. Therefore, biomass is said to be more biodegradable compared to coal. The gasification temperature of biomass is between (650°C - 1200°C) which is much lower than coal (1300°C - 1600°C). High energy will be consumed in high gasification operating temperature especially when steam is used as the gasifying agent [28].

Size, shape and structure of biomass affect the rate of gasification. For maximum rate of gasification and better controlling temperature, small size of biomass is preferable [29]. The composition and impurities of the syngas produced in the gasification depends on biomass feedstock, gasifier design, gasifying agent and gasification condition mainly temperature, equivalent ratio (ER), steam to biomass ratio and pressure [20, 30-31]

1.2. Entrained Flow Gasifier

Entrained flow gasifiers have the ability to gasify practically any fuels, but fuel with lower moisture and ash content are favored to reduce oxygen consumption. Due to the short residence time, high temperatures are required to ensure a good carbon conversion [32-33] and therefore entrained flow gasifiers have a high oxygen demand. High temperature also results in CO and H₂ rich gas. Soot may be formed depending on the type of fuel [33]. This reactor provides an intensive contact between the gasifying agent and biomass which result in higher conversion and higher reaction rates [20].

One of the disadvantages of entrained flow gasifiers is that the fuel particles should be very small to be completely converted in the short time that they reside inside the hot gasifier. This is especially true for solid biomass since the biomass is hard to grind to small particle sizes and this is one of the main technical barriers connected with entrained flow gasification of biomass [34].

Compared with moving bed gasifiers and fluidized bed gasifiers, entrained flow gasifiers operating at very high temperatures, can produce a clean, almost tar-free, product gas and in short residence time can achieve a high load throughput. The advantages of entrained flow gasifiers are it has a simple structure, no catalyst is required, the tar yield is low, control of the gaseous components is easy, and various kinds of biomass can be used as feedstock are available as feedstock [28].

Many researchers have studied the effect of temperature on CO₂ concentration, where both coal and biomass gasification shows similar trends. At low temperature, the CO₂ concentration is high but start decreasing when the operating temperature of the gasifiers was increased [35]. This trend is due to the
increase of the endothermic reaction such as Boudouard reaction which involves the consumption of CO$_2$ [36]. For biomass gasification, the researcher found that the trend is the same as the coal gasification [37-38]. However, the carbon conversion is slightly higher for biomass gasification than that of the coal gasification due to the presence of high volatile matters in biomass. On the other hand, in biomass gasification, the increase of temperature will reduce the calorific values of the product gas due to the decrease in the concentration of hydrogen bond [39]. Another parameter that is highly affected by the operating temperature is the cold gas efficiency (CGE). For both biomass gasification and coal gasification, the CGE were increased with the increase of temperature [37-38]. However, its value in biomass gasification is more than that of coal gasification because of a higher yield in the gaseous product during biomass gasification as observed by [39].

The oxidant used in gasification process either in biomass gasification or coal gasification will affect the production of syngas. Traditionally, the common gasifying agent use in gasification process is air which content O$_2$ and N$_2$. From the study reported by [40], when the air become the oxidising agent, the syngas produced composition is 16.7% for H$_2$, 22.3% for CO, 9.61% for CO$_2$ and 50.8% for N$_2$. When the CO$_2$ replace the air as the oxidising agent for gasifiers, the composition for the syngas produced have change to 16.4% for H$_2$, 56.3% for CO, 27.3% for CO$_2$ and 0.06% for N$_2$ [40]. This shows that CO production was decreased while the CO$_2$ was increased.

There is huge potential in exploring the utilization of one of the greenhouse gases, CO$_2$ as a gasifying agent, and biomass waste, both of which are unwanted. In this study, the gasification of biomass with CO$_2$ by using palm oil EFB will be carried out at different temperatures and different oxidant to feed (OTF) ratio in which various concentration of CO$_2$ as oxidant will be varied. This is to determine the optimum temperature and OTF ratio for syngas production by means of biomass gasification.

2. Methodology

2.1. Biomass Feedstock and Characterisation

The empty fruit bunches are collected from an oil palm mill in Lepar Hilir. It has a relatively high moisture content of about 60%, hence it was cleansed and dried prior to the experiments. The ultimate analysis was done by using a CHNS/O Analyzer (model LECO TruSpec CHN, USA) following the ASTM D-5291 method. The proximate analysis of the sample to determine its moisture content (dry basis), volatile matter, fixed carbon and ash were determined using a thermo gravimetric analyser (model Mettler Toledo, TGA/SDTA851, USA). The heating value of EFB was determined by burning a weighed sample in an adiabatic oxygen-bomb calorimeter (model Parr 1341, USA) following the ASTM D240 method, while a Micromeritics helium pycnometer (AccuPyc II 1340) was used to measure the volume and apparent density of the sample. The results of the analysis are listed in Table 2.

| Table 2. Properties of EFB |
|----------------------------|
| **Proximate Analysis (wt %)** | **Ultimate Analysis (wt %), daf$^a$** |
| Moisture | 5.977 | C | 43.518 |
| Volatile matter | 67.58 | H | 7.255 |
| Fixed carbon | 5.893 | O$^b$ | 45.896 |
| Ash | 20.48 | N | 3.041 |
| HHV (MJ/kg) | 18.67 | S | 0.290 |
| Density (kg/m$^3$) | 1390.8 |

$^a$ Dry and free ash; $^b$ The oxygen (O) content was determined by difference
2.2. The Gasification Experiment Setup

The entrained flow gasifier was designed and built in our laboratory. As shown in Figure 2, the height of the gasifier is about 50cm and the diameter is 4.5cm. The gasification test of EFB was carried out with entrained flow reactor. In a typical test, 20 g dried EFB samples without catalyst was loaded in the reactor. The carbon dioxide was used as gasification agent and nitrogen as carrier at a constant volume flow rate of 18 LPM. The reactor was heated from room temperature to a temperature range of 700°C-900°C. Once the temperature was reached, the gas flow was switched from N₂ to CO₂, the solid and water feeds were switched on. A constant gas composition was reached after 10-15s of starting the feeding. All 5 different oxidant to fuel ratio ranging from 0.2-1.0 will undergo five different operating temperatures which are 700, 750, 800, 850 and 900°C. The produced gas was collected after passing through a condenser. After the termination of the gasification process, the fraction consist of solid material recovered from the reactor bottom was defined as solid residue.

![Figure 2. Schematic diagram of gasification system](image)

2.3. Product Analysis

The product gas was primarily analysed using the Thermal Conductivity Detector (GC-TCD). From the values obtained, all other analysis may be done. The carbon conversion, X represents the percentage (%) of total carbon in the gasifier feedstock which is converted to product gases, which contain carbon (i.e. CO, CO₂, CH₄). Equation (1) is used to determine the conversion.

\[
\text{Conversion} = \frac{\text{Total mol C (%)} \text{ in CO, CO}_2 \& \text{CH}_4}{\text{mol C (%)} \text{ obtained during ultimate analysis}}
\]  

(1)

The higher heating value (HHV) of the product gas is calculated based on Equation (2), based on the heating values from [42], and the obtained values were further used to calculate the CGE of the product gases as in Equation (3) [41].

\[
\text{H}_2 = 12.76 \text{ MJ/m}^3; \text{ CO} = 12.63 \text{MJ/m}^3; \text{CH}_4 = 39.76 \text{MJ/m}^3 \ [42]
\]
Since only H\textsubscript{2}, CO and CH\textsubscript{4} are combustible, the HHV of syngas is the calorific value of these three gases:

\[ \Delta H = (12.76 \text{ MJ/m}^3 \times \text{H}_2 \text{ vol } \%) + (12.63 \text{ MJ/m}^3 \times \text{CO vol } \%) + (39.76 \text{ MJ/m}^3 \times \text{CH}_4 \text{ vol } \%) \]  \hspace{1cm} (2)

## 3. Results and Discussion

### 3.1 \textit{H}_2 volume flowrate

In this work, the effect of OTF on the production of H\textsubscript{2} gas was studied from 0.2-1.0 ratio. It can be observed that H\textsubscript{2} is highly affected by the OTF ratio that used in gasification process. Figure 3 illustrates the trends of H\textsubscript{2} production with the increasing of OTF ratio for different operating temperature. It is observed that for temperature 900°C, H\textsubscript{2} is increased from 1.2\% to 2.2\% with the increase of OTF ratio from 0.2 to 0.8 and slightly decreased at higher OTF ratio. Similar trend was observed by [43] whereby the H\textsubscript{2} concentration declined with the rising of CO concentration in the gasification process, although the observation was for high OTF ratios, which is between 0.8 and 1.0. From this, it can be concluded that H\textsubscript{2} production will increased when low OTF ratio was applied and the value will be decreased when higher OTF ratio used in gasification process.

![Figure 3. Effect of OTF on volume flow rate of H\textsubscript{2} at different operating temperature](image)

### 3.2 CO volume flowrate

Figure 4 illustrates on how CO is affected by the increased of the OTF ratio from 0.2-1.0. From the figure, it can be observed that the CO production is slightly decreasing for temperature 700°C to 800°C when OTF ratio reached 0.8. On the other hand, when the operating temperature reached 900°C, CO production was increased from 0.73\% to 1.0\%. Similar finding was also observed by [43] studying the effect of CO\textsubscript{2} as the oxidizing agent in biomass gasification. The operating temperature must be higher than 800°C to ensure that the Boudouard reaction (\(C + CO_2 \rightarrow 2CO\)) becomes the more prominent reaction in this biomass gasification.
3.3 CO$_2$ volume flowrate

The use of CO$_2$ as the gasifying agent will affect the vol% of the CO$_2$ produced in this study. The trend is obtained from the study in which the effect of vol% of CO$_2$ with the increasing of OTF ratio is shown in Figure 5. For temperature 850°C-900°C, the concentration of CO$_2$ is increasing from OTF 0.2 until 0.8 and decrease when approaching 1.0. However, for temperature 700°C to 800°C, the concentration of CO$_2$ nearly constant after OTF 0.8.

Hanaoka et al. (2012) studied the gasification of biomass and found that the CO$_2$ composition will rise when the CO$_2$ percentage in gasifying agent increase. In this study, it was also determined that the vol% of CO$_2$ will increase with the increase of OTF ratio applies during gasification process. Although the CO$_2$ consumed in the Boudouard reaction to produce CO, the high amount of CO$_2$ gas feed to the reactor recover the loss of CO$_2$ in the reaction.

3.4 HHV

HHV of produced gas from gasification process was determined using Equation (2). The graph of HHV versus temperature for different OTF ratio is shown in Figure 6. The trend shows that the increment of OTF ratio from 0.2 to 1.0 increased the HHV value of the syngas produced. This HHV value is strongly related to the amount of H$_2$, CO and CH$_4$ that obtained. As the amount of CO and CH$_4$ increase by the Boudouard reaction and methane production reaction at higher OTF ratio, it can be concluded that the HHV of produced syngas will increase with increase of OTF ratio.
3.5 $H_2/CO$ ratio

$H_2/CO$ ratio is one of the important parameter in the analysis of the syngas produced from biomass gasification. The trends obtain from this study are shown in Figure 7. From the figure, the $H_2/CO$ ratio was increased when the OTF was increased from 0.2 to 0.8. However, this value decreased drastically at higher OTF. This trend is almost similar to the trend obtain in the effect of OTF on $H_2$ volume percentage. This suggests that the $H_2/CO$ ratio is related to the amount of $H_2$ produced from this gasification process. In addition, the trends obtained can be related to the moisture content of the feedstock. At higher temperature of gasifier, the moisture content decreased thus decreased the production of $H_2$ from the gasification process.

3.6 Carbon conversion

Fuel conversion was determined by dividing the total amount of carbon content in CO, CO$_2$ and CH$_4$ produced from gasification process with the amount of carbon content in raw EFB from its ultimate analysis. The trend for the fuel conversion with the increase OTF ratio for different operating temperature is shown in Figure 8. It was found that the fuel conversion is positively affected by the increase of OTF ratio. This is due to the fact that higher OTF ratios will increase the production of the combustible gases: CO, CO$_2$ and CH$_4$. Higher production of these gases will cause the higher fuel conversion for this gasification. From the result obtain, volume flow rate of CO was increased due to the Boudouard reaction that is more prominent at higher operating temperature.
Figure 8. Effect of OTF on carbon conversion at different operating temperature

Other than that, the use of CO\textsubscript{2} as the oxidising agent generates the higher production of CO that effect the fuel conversion for this process. The amount of carbon present in the biomass used in the study can also affect the value of fuel conversion. The lower the carbon content in the feedstock will cause the higher value of carbon conversion for this process.

4. Conclusion

Conversion of biomass to thermochemical conversion especially by gasification process could be one of the promising methods to optimise the utilization of this abundant and valuable source of wastes.

It is important to study the best condition for gasification process in order to ensure the maximum composition of syngas produced. From this study of the influence of OTF ratio and operating temperature on biomass gasification was investigated. It can be concluded that these two parameters have significant effects to the production of syngas. The biomass gasification process using CO\textsubscript{2} must be conducted at high gasifier temperature which is 900°C and OTF ratio 1.0. This is to ensure all the requires reaction involve in this gasification process such as the Boudouard reaction, water gas reaction and also the methane production reaction can take place dominantly thus resulting higher syngas production.

Further research should be carried out to determine the highest syngas production among several oil palm wastes include palm kernel shell and oil palm frond. Furthermore, the continuous effort will contribute to the enrichment of new knowledge and technology whereas at the same time helps to preserve nature for the future in a more sustainable way.

Acknowledgement

This project was supported by the Ministry of Higher Education Malaysia FRGS (RDU140134). The authors also thank the Faculty of Chemical Engineering and Natural Resources, Universiti Malaysia Pahang, for providing the lab space to conduct the trials.

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