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Downdraft Gasification of Oil Palm Frond: Effects of Temperature and Operation Time

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ABSTRACT

Currently produced more than 40 million tons a year, only a small portion of oil palm frond is used as domestic animals forage and as raw material in small-scale furniture industry, while the rest is left at the plantation floor to naturally decompose. This study introduces oil palm frond as a solid biomass fuel for gasification to produce synthesis gas that can be utilized for heat and energy generation in a cleaner and more efficient manner than direct combustion. Oil palm frond was gasified in the downdraft gasifier at 700 to 1000°C reactor temperature with a controlled air supply of 180 to 200 L min^{-1}. The effects of reactor temperature and operation time to the quality of syngas produced from oil palm frond downdraft gasification were investigated. At a calorific value around 18 MJ kg^{-1}, oil palm frond was found to produce synthesis gas that sustainably burnt in air with a higher heating value of around 5 MJ N^{-1} m^{-3}. Oil palm frond was found to be optimally producing syngas with desired energy content at a reactor temperature range of 700-900°C and within the first 45 min of gasifier operation.

Key words: Biomass, fuel, gasification, oil palm frond, syngas

INTRODUCTION

Until the petroleum industry was introduced in the late 1800s, biomass has been exploited as the main energy source for heat and power generation. A quick depletion of the global petroleum resources in the recent years has been observed while demands for heat and power increase steadily by the year. With the petroleum resources estimated to disappear completely in less than 50 years (Shuit *et al*., 2009), scientists and researchers worldwide introduced several renewable and alternative energy sources in which one of them is biomass. While biomass is most common as solid fuels to large energy facilities, its exploitation in small scale application can be even more fascinating mainly for the higher prospect for heat recovery, low complexity in raw materials supply and low impacts to the environment. Moreover, small plants are applicable to a wider range of industry and consumer users than large plants, adding up to its generous versatility as a renewable source for heat and power generation. As in Malaysia, a tropical country located close to the equator, biomass supply is in abundance. Being currently the second largest palm oil producer responsible for 43% of the world's supply, Malaysia utilized more than 4.5 million hectares of its land for the cultivation of oil palm trees (Malaysia Palm Oil Board, 2011). With an increasing trend in the awareness of biomass potential as an alternative energy resource, the palm oil industry has emerged to be an attractive platform for continuous and large biomass supply as depicted by

Abdullah and Yusup (2010). Common examples of biomass from oil palm industry are Palm Oil Mill Effluent (POME), Empty Fruit Bunch (EFB), fiber, shells, kernels, trunks and oil palm fronds as widely discussed by Faizal *et al.* (2010), Wan *et al.* (2010), Abdullah *et al.* (2011) and Razuan *et al.* (2010). Oil palm frond was not given much attention to unlike other biomasses produced by the oil palm tree. Other than being utilized as ruminant feedstock for cattle as reported by Atil (2004) and as a raw material in small-scale wood and furniture industry, a large amount of oil palm frond would normally be left on the plantation floor as a natural fertilizer once pruned or used as nutrient sources for the cultivation of young palms according to Haron *et al.* (2007).

Recent studies on oil palm frond as a raw material for ethanol production as reported by Yutaka (2007) and biomass briquette by Nasrin *et al.* (2008) have been presented and discussed. This realization of oil palm frond as a biomass source led to a few studies including this one to have been established to introduce alternative endings to oil palm frond as a biomass with potential values. With biomass gasification re-emerging popularity among researchers and enthusiasts worldwide in the pursuit to create and promote the awareness in green technology, oil palm frond is seen to be a potential candidate based on its abundant supply and considerable energy content to be processed as a solid fuel for gasification. Efforts in studying oil palm frond gasification by simulation and experiment approaches was reported by Atnaw *et al.* (2011), bearing a potential result where oil palm frond might be a prospective biomass fuel for heat and energy generation. Similarly, a torrefaction attempt on oil palm frond was reported by Sulaiman and Anas (2012).

This study intended to utilize oil palm frond in downdraft gasification process, in which the effects of the reactor temperatures and operation time to the quality of the produced syngas were studied. The outcome of this study would enable oil palm frond to be utilized as a solid biomass fuel for gasification at a larger scale where its practicality can be further observed and studied for actual application. The public awareness about gasification and its benefit may be increased mainly due to the heightened interest in green technology and the world's fuel crisis. The promising potential of oil palm frond as gasification fuel would be one of the biggest solution to Malaysia's yearly energy expenses on coal and other fossil fuels for heat and energy generation when applied. The outcomes of this present research would also generate a few more studies of oil palm frond as a biomass fuel for other applications, if not for gasification, thus promoting more intellectual awareness of oil palm frond as a new hope as a biomass fuel source.

MATERIALS AND METHODS

The study is carried out by observing the effects of temperature and gasifier operation time to syngas production in a downdraft gasifier. Temperatures were taken at six localized areas inside the downdraft gasifier in order to determine the drying, pyrolysis, combustion and reduction zones. Gas analysis was done continuously using a gas analyzer for syngas composition and the readings were recorded for comparisons. A downdraft gasifier was used in the study to gasify oil palm frond to syngas with a controlled amount of air.

Measuring instruments: Six type-N thermocouples were connected vertically on the gasifier body and their cables were connected to an 8-port USB hub that delivered real-time readings to a computer unit for monitoring and recording purposes. An online gas analyzer capable of tracing CO, CO_2, H_2, N_2 and CH_4 in syngas was connected to the outlet pipe of the gasifier. It continuously analyzed syngas components in a real time basis and the compositions of syngas were also displayed in the computer for monitoring and recording purposes.

Gasifier specification: The gasifier used for the experiment was a laboratory-scale stationary, batch-operated 50 kWh fixed-bed downdraft type. The arrangement of the gasifier system is shown in Fig. 1. Air was supplied into the gasifier by means of blowing using a 250 W vortex blower and the amount of supplied air was controlled using a ball valve and a bypass point and monitored using a pitot tube and a water manometer. The full capacity of the gasifier was 12 kg for 2.5-5.0 cm cubic oil palm frond blocks with 70% compact factor.

Feedstock specification: Pre-processed oil palm frond fuel in block form was prepared and utilized in the experiment. Every part of oil palm frond was utilized except for the leaflets in order to maintain a uniform fuel particle size and morphology. Averagely, the dimension of each fuel block was 2.5-5.0 cm in cubic shape. The fuel was processed from green oil palm frond and was pre-dried to achieve the desired moisture content of 12±2%. The calorific value of oil palm frond fuel was found to be 17.65 MJ kg^{-1} by average on dry basis.

Gasification setting: The downdraft gasification of oil palm frond was conducted within a known operation range for oil palm frond fuel. The supplied air into the gasifier was controlled in the range of 180-200 L min^{-1} to keep the reactor temperature in between 700-900°C. Conducted studies have shown that this setting was the most optimal for the gasification of oil palm frond fuel as described previously. The reactor temperature was controlled by means of regulating the air supply into the gasifier. The intended gasifier operation time was 1 hour before refueling was required.

Preheating procedure: Prior to each test, the reactor was first preheated to prepare for gasification. Preheating was done by burning a pilot fuel that comprised of shredded paper, garden refuse and rejected oil palm frond fuel from the fuel processing stages in the gasifier to bring up the reactor temperature to more than 500°C. This process was important to form a layer of char bed above the reactor grate. With preheating, syngas was produced at a shorter time (5-10 min) than

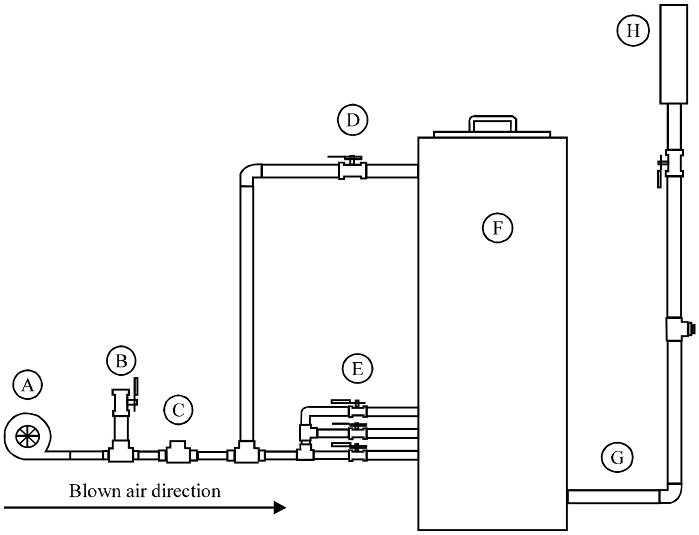

Fig. 1: Downdraft gasifier assembly, A: Vortex air blower, B: Air bypass outlet, C: Primary air route, D: Primary air route, E: Secondary air route, F: Downdraft gasifier, G: Gas exhaust pipe, H: Gas flare point

without (15-20 min) and the combustion of oil palm frond fuel was found to be steadier and less problematic. The positive effects of gasifier preheating can be explained by considering the autoignition temperature of woody biomass including wood that is around 250-300°C as thoroughly discussed by Baker (1983), Boonmee and Quintiere (2002) and Cao *et al.* (2006). Following preheating, thermochemical reactions occurred almost as instantly on freshly-loaded oil palm frond fuel blocks due to rapid heating of fuel, resulting into a quicker transition from instantaneous drying to pyrolysis. Such transition made syngas to produce faster than without preheating. Additionally, excess tar deposits on the internal reactor and pipe walls from previous operations were discovered to be consumed in the heat, showing another advantage of preheating in the caretaking of the gasifier system. This was due to the thermal cracking of tar at a temperature of 700°C to above 1000°C according to Milne *et al.* (1998).

RESULTS AND DISCUSSION

Influence of reactor temperature: The influence of reactor temperature on the quality of syngas from the downdraft gasification of oil palm frond was investigated by comparing the components and the calorific values of syngas produced at various reactor temperatures. Table 1 shows their average values at different reactor temperature ranges. In Table 1, CO and H_2 were found to produce in an increasing manner with increasing reactor temperature, although, the production of. H_2 was found to drop following 850°C point. The highest level of CO produced in syngas was found to be 28.21% at 1100-1200°C temperature range while H_2 hit the maximum of 11.29% at 800-900°C temperature range. CO_2 production showed a dropping pattern as the reactor temperature rose from a maximum of 15.19% to a minimum of 7.82%. CH_4 production however was found to be slightly increasing with increasing temperature, although with very less significance, at a range of 0.39-1.29%. The production pattern of the gas components in syngas was found to be in agreement with the works of Sulaiman *et al.* (2011), Son *et al.* (2011) and Nipattummakul *et al.* (2011) where similar trends can be observed in the gasification of oil palm frond and other biomass. The percentage of CO and H_2 syngas however was noted to be lower than the amounts obtained from the gasification of wood as done by Debrand and Hahn (1978) and Sivakumar and Mohan (2010).

The lower calorific value of syngas (LCV_{syngas}) and the H_2:CO ratio are shown in Table 2. The results showed that H_2:CO ratio decreased but the Cold Gas Efficiency (CGE) increased with increasing LCV_{syngas} and reactor temperature.

Table 1: Gas components in syngas produced from downdraft gasification of oil palm frond chips as a function of reactor temperature range

	Gas components (vol. %)			
Reactor temp. (°C)	CO	CO_2	CH_4	H_2
300-400	9.23	15.19	0.39	4.71
400-500	10.39	15.08	0.84	7.78
500-600	11.70	13.80	0.67	5.95
600-700	13.79	13.70	1.03	8.79
700-800	15.61	13.80	1.03	9.19
800-900	20.80	12.06	1.35	11.29
900-1000	23.33	10.38	1.23	10.20
1000-1100	26.12	8.81	1.32	9.30
1100-1200	28.21	7.82	1.29	9.59

Table 2: Characteristic of syngas produced from downdraft gasification of oil palm frond chips as a function of reactor temperature range

Reactor temp. (°C)	Lower calorific value (MJ N^{-1} m^{-3})	H_2:CO ratio	Cold gas efficiency (%)
300-400	1.99	0.51	27.65
400-500	2.73	0.75	37.96
500-600	2.59	0.51	36.03
600-700	3.39	0.64	47.11
700-800	3.68	0.59	51.15
800-900	4.77	0.54	66.27
900-1000	4.91	0.44	68.19
1000-1100	5.19	0.36	72.12
1100-1200	5.49	0.34	76.28

H_2:CO ratio achieved a maximum of 0.75 at 400-500°C temperature range while the LHV maximum of 5.49 MJ N^{-1} m^{-3} was achieved at 1100-1200°C. H_2:CO ratio was observed to grow at a steady incline but the LHV values were rather scattered along the decline with increasing temperature. As to compare with existing literature, Vera *et al.* (2011) in an experimental study reported that the LCV of syngas dropped with increasing temperature while Khadse *et al.* (2006) reported the opposite using a MATLAB prediction model, in which the latter showed a similar trend observed in the dynamic LCV_{syngas} pattern shown in Table 2. The reason behind the increment of LCV may be explained using the following correlation:

$$LCV_{syngas} = I(LCV_n \times Vol.\ \%_n) \tag{1}$$

where, LCV_{syngas} is the total lower calorific value of syngas while LCV_n is the specific lower calorific value of a gas component species i.e., CO and CO_2. The summation of the lower calorific values of all gas component species (CO, CO_2, H_2 and CH_4) will bear LCV_{syngas}. The typical LCV used were: 13.1 MJ N^{-1} m^{-3} for CO; 0 MJ N^{-1} m^{-3} for CO_2; 37.1 MJ N^{-1} m^{-3} for CH_4 and 11.2 MJ N^{-1} m^{-3} for H_2.

The increment in LCV_{syngas} with increasing reactor temperature was speculated due to the increasing concentration of CO in syngas, where the LCV of CO is slightly higher than that of H_2, hence also explained why LCV_{syngas} still increased even when with reducing H_2 amount in syngas: the superiority of energy content of CO at increasing concentration overcame the loss in syngas energy due to the reduction of H_2 in syngas as the reactor temperature rose to above 1000°C. While this may be beneficial to increase LCV_{syngas}, the combustibility of syngas may be compromised due to the high CO concentration for the fact that CO, although combustible, is also a non-supporter of combustion. Higher H_2 concentration in syngas is therefore still favorable for this reason. This increasing amount CO compared to decreasing H_2 with increasing reactor temperature also caused the H_2:CO ratio to radically drop.

The cold gas efficiency of syngas (CGE) is also shown in Table 2. The CGE values were calculated using the following correlation:

$$CGE = \frac{V_{syngas} \times LCV_{syngas}}{m_{OPF} \times LCV_{OPF}} \tag{2}$$

where, V_{syngas} is the flow rate of syngas leaving the reactor, m_{OPF} is the mass feed rate of oil palm frond fuel in the reactor and LCV_{syngas} and LCV_{OPF} are the lower calorific values of syngas and oil palm frond, respectively. Due to the limitation to measure the actual V_{syngas} owing to the incapability of the existing measuring instrument, it was estimated that every kilogram of oil palm frond produced 2.5 m^3 of gas by average amount of gas produced from 1 kg or biomass according to the GEK developers (AllPowerLabs, 2010) while m_{OPF} was estimated to be 10 kg h^{-1}. LCV_{syngas} were calculated from syngas compositions while LCV_{OPF} was defined to be 17.85 MJ kg^{-1} by average.

As shown in Table 2, it was observed that CGE increased with increasing reactor temperature, mainly due to the increment in syngas energy as attributed to the rising concentration of CO. The highest CGE value was found to be 76.28% at a reactor temperature range of 1150±50°C. This observation was related to the increasing amount of CO in syngas as discussed previously. To note that CGE was mostly in between 50-70%, it showed a good indication that the pyrolysis process inside the reactor was good enough to extract volatiles from oil palm frond fuel as concluded by Kennedy and Lukose (2006). The ranges of syngas properties at a selected temperature range of 700-900°C where gasification is commonly carried out are shown in Table 3. The rank of the highest to lowest amount of componential gases in syngas is found to be: CO, CO_2, H_2 and CH_4, in that order. The ranges of LCV, H_2:CO and CGE were found to be acceptable and within the common range of that of syngas. The H_2:CO ratio of 0.54-0.59 made it ideal for OPF-derived syngas via downdraft gasification to be used as fuel in internal combustion engines.

Influence of operation time: The influence of operation time to syngas characteristic has been an important interest to this study in order to determine the maximum operation time until the gasifier needs to halt the supply of syngas for refueling mainly due to decreasing syngas quality. The characteristic of syngas was monitored by the concentration of its gas components, Lower Calorific Value (LCV), H_2:CO ratio and Cold Gas Efficiency (CGE).

Table 4 shows the concentration of gas components in syngas as a function of gasifier operation time. CO was observed to peak to 21.69% at minute 75 after a steady climb before experiencing a sharp drop towards the end of operation. H_2 showed almost the same pattern where its concentration peaked to 10.77% at 85 min before experiencing a drop following that period and is in accordance with the finding in the work of Ganan *et al.* (2006) on vine shoots. CO_2 however experienced very less change in concentration except at 55 min where it suddenly peaked to 14.20%, believed to be a result of a temporary bridging, before stabilizing again and then gently increased after 75 min towards the end of operation. CH_4 experienced relatively almost no change at all in concentration along the gasification period and was observed to reduce in concentration after 95 mins of operation. The range of concentration for each gas components was found to be 8.16-21.69% for CO, 10.84-15.60% for CO_2, 0.37-1.49% for CH_4 and 4.63-10.77% for H_2. Overall, the trend was found to be similar with the pyrolysis and combustion results of oil palm stone and palm kernel cake by Razuan *et al.* (2010).

Table 3: Characteristic of syngas produced from the downdraft gasification of oil palm frond chips

Parameter	Values
Reactor temp. (°C)	700-900
CO concentration (vol. %)	15.61-20.80
CO_2 concentration (vol. %)	12.06-13.80
CH_4 concentration (vol. %)	1.03-1.35
H_2 concentration (vol. %)	9.19-11.29
Lower calorific value (MJ N^{-1} m^{-3})	3.68-4.77
H_2:CO ratio	0.54-0.59
Cold gas efficiency (%)	51.15-66.27

Table 4: Gas components in syngas produced from downdraft gasification of oil palm frond chips as a function of gasifier operation time

	Gas components (vol. %)			
Time (min)	CO	CO_2	CH_4	H_2
5	18.73	15.34	1.49	9.87
15	17.49	12.52	0.98	8.83
25	17.27	12.43	1.32	10.00
35	16.30	12.00	1.09	8.41
45	17.95	12.02	0.99	8.53
55	17.73	14.20	1.39	9.25
65	19.36	11.72	1.27	9.94
75	21.69	10.84	1.19	10.18
85	20.43	11.81	1.22	10.77
95	15.45	13.02	0.64	8.22
105	10.74	14.73	0.37	4.97
115	8.16	15.60	0.40	4.63

Table 5: Characteristic of syngas produced from downdraft gasification of oil palm frond chips as a function of gasifier operation time

Time (min)	LCV (MJ N^{-1} m^{-3})	H_2:CO ratio	CGE (%)
5	4.37	52.58	60.71
15	3.86	50.65	53.64
25	4.13	64.57	57.30
35	3.69	64.12	51.31
45	3.89	53.78	53.98
55	4.62	73.77	64.19
65	4.37	69.38	60.70
75	4.67	47.22	64.90
85	4.60	52.83	63.92
95	3.37	52.56	46.84
105	2.22	46.36	30.79
115	1.84	56.76	25.60

LCV: Lower calorific value, CGE: Cold gas efficiency

Table 5 shows the values of Lower Calorific Value (LCV) of syngas, the H_2:CO ratio and the Cold Gas Efficiency (CGE) as functions of operation time. LCV of oil palm frond-derived syngas was found to be in the range of 1.84-4.67 MJ N^{-1} m^{-3} while the H_2:CO ratio was found to be in the range of 46.36-73.77. The highest LCV and H_2:CO were found to be 4.67 MJ N^{-1} m^{-3} and 73.77 at min 75 and 55, respectively. Both LCV and H_2:CO ratio showed a climbing trend before dropping towards the end of the gasifier operation. LCV experienced the most reduction after around 90 min of operation, hitting the lowest point of 1.84 MJ N^{-1} m^{-3}, while the H_2:CO ratio did not give a very conclusive pattern of change along the gasification period, although the polynomial trend line suggested a smooth reduction following the 60th minute of operation with only 1.74% difference from the average of 57.04. The polynomial trend line for LCV showed a steep drop at nearly the same time frame. The reduction in LCV was mainly due to the decreasing amounts of CO and H_2 towards the end of the operation where as the oil palm frond fuel has been consumed to a minimum level, the air-fuel ratio increased to nearly and more than 1.0, transitioning the otherwise substoichiometric gasification to a complete combustion. This caused CO_2 to be produced instead of H_2 and CO, leading to the drop in the values of LCV and H_2:CO ratio towards the end of operation. Cao *et al.* (2006) discussed the similar observation, where LCV of syngas dropped mainly due to the decreasing amount of combustible components in syngas.

The Cold Gas Efficiency (CGE) of syngas as a function of gasifier operation time is shown in Table 5. Table 5 showed that CGE rose from the start of the operation and peaked at min 55 before experiencing a steady reduction towards the end of the operation. The highest CGE value was found to be 64.9% at mine 75 while lowest was 25.6% at min 115. For the first 80 min of operation the CGE was found to be above 50% which was considered to be an acceptable range. By average, the CGE for the entire duration of gasifier operation was found to be 52.82%. This observation rectified the needs for the operation time to be limited to a maximum of 60 min to ensure a steady supply of quality syngas.

CONCLUSION

In conclusion, it was found that the change in syngas characteristic due to variations in reactor temperature critically contributed to the gasifier operation demand; in order to produce good quality syngas from oil palm frond, the temperature of the reactor has to be kept in between the range of 700 to 900°C while consecutively keeping the H_2:CO ratio at above 0.5. Although, at a higher temperature LCV and CGE improved significantly, the ignitability of syngas was compromised due to the high amount of CO in syngas, due to its nature as not a non-supporter of combustion. The designed operating duration for the gasifier was intended to be 60 min and it was discovered that the gasifier met the intended specification. Following the operation period of above 60 min, the quality of syngas in terms of composition and energy content reduced to which it became less effective to futile to be utilized to generate heat and power. For this reason, the operation of the gasifier has to be limited to only 60 min for each full capacity run until refueling is required.

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