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Fluidised Bed Gasification and Chemical Exergy Analysis of Pelletised Oil Palm Empty Fruit Bunches

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The National Biomass Strategy was envisioned to foster the efficient valorisation and management of Oil Palm Waste (OPW) in Malaysia. However, the proposed Circular Energy Economy is hampered by poor OPW fuel properties, inefficient conversion techniques, and process design. This study explored the valorisation of Oil Palm Empty Fruit Bunches (OPEFB) Briquettes through fluidised bed gasification with the aim of exploiting the superior qualities of pelletised biomass and excellent reactor dynamics of fluidised beds. Gasification of OPEFB Briquettes was examined from 600 – 800 °C and equivalence ratio, ER is 0.20 – 0.25 under atmospheric pressure. The fuel properties and chemical exergy of OPEFB briquettes were characterised. The gasification of OPEFB briquettes produced high biochar yield and bio syngas with higher heating value from 1.15 – 3.05 MJ/m^3 whereas the Cold Gas Efficiency (CGE) and Carbon Conversion Efficiency (CCE) ranged from 6.54 – 17.34 % and 43.37 – 78.16 %. Bed agglomeration and defluidisation typically encountered in pulverised OPEFB gasification were minimal during the gasification of OPEFB briquettes. In conclusion, the results demonstrated that OPEFB Briquettes gasification is a practical route for valorising OPW into renewable energy and sustainable fuels.

1. Introduction

The National Biomass Strategy (NBS-2020) was established in 2013 to stimulate the efficient valorisation of large quantities of Oil Palm Waste (OPW) generated annually from the palm oil industry in Malaysia (AIM, 2013). Current conversion technologies are outdated, inefficient and unsustainable (Umar et al., 2014) resulting in greenhouse gas (GHGs) emissions (Reijnders and Huijbregts, 2008), waste disposal and management problems (Nyakuma et al., 2012). The valorisation of OPW into clean energy and chemical fuels is hampered by poor biofuel fuel properties of OPW (Ravindra and Sarbatly, 2013) including high moisture content, alkali ash composition, low calorific value and bulky size (Kelly-Yong et al., 2007). The efficient utilisation of OPW waste as boiler fuel for heat, steam and electricity generation in oil palm mills remains a challenge for the industry (Shuit et al., 2009).

Consequently, researchers have explored different low-temperature conversion technologies (LCT) namely; pyrolysis (Sulaiman and Abdullah, 2011), torrefaction (Uemura et al., 2013) liquefaction and hydrothermal carbonisation (HTC) (Jamari and Howse, 2012) for valorising OPWs. The results have demonstrated that valorisation of OPW through LCTs predominantly results in solid biofuels (SBF) and bio-oils that require further downstream processing before utilisation in current energy generation infrastructure. LCTs are typically batch processes which present significant challenges for upgrades to industrial scale (Gertenbach and Cooper, 2009).

High-temperature (HT) processes such as combustion have been proposed by researchers for valorisation of OPW (Madhiyanon et al., 2012). The results demonstrated that combustion typically results in ash deposition, severe fouling, slagging, and meltdown, combustion of OPWs yields low heating value flue gases, and the emission of toxic aerosols and PAHs.

Gasification presents opportunities for the production of high heating value syngas (or fuel gas mixtures) (Costa et al., 2014), renewable energy (Ruoppolo et al., 2013) and green chemicals (Basu, 2010). Consequently, researchers have explored HT gasification of OPEFB in bench-scale (Mohammed et al., 2012) and pilot scale

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gasifiers (Lahijani and Zainal, 2011) for energy production. The results established that HT OPW gasification results in agglomeration, fouling and defluidisation (Lahijani and Zainal, 2014) due to poor fuel properties (Nyakuma et al., 2014a). These challenges can be addressed by upgrading OPW fuel properties through pre-treatment techniques such as briquetting or palletisation (Nyakuma et al., 2014b). Similarly, appropriate gasifier selection and process design practices such as LT gasification can be utilised.

The main objective of this paper is to explore the valorisation of pelletised Oil Palm Empty Fruit Bunches (OPEFB Briquettes) through LT fluidised bed gasification for clean energy and solid biofuels production. This is aimed at exploiting the superior fuel qualities of pelletised biomasses and excellent reactor dynamics of fluidised bed gasifiers for efficient OPEFB Briquettes valorisation. The study also presents the chemical fuel properties and exergy analysis of OPEFB Briquettes.

2. Experimental

The OPEFB Briquettes were acquired from Felda Semenchu Oil Palm Mill in Johor, Malaysia. Prior to characterisation, the briquettes were pulverised and sifted into 250 µm sized particles. Next, it was subjected to ultimate, proximate and calorific characterisation to examine its physicochemical properties. The thermokinetic properties of the briquettes were examined in our previous work (Nyakuma et al., 2015). Next, chemical exergy was calculated from elemental analysis and heating values based on Eq(1) - (3) (Bilgen, 2016);

$$\mathrm{E^{CH}} = \beta \times \mathrm{LHV} \tag{1}$$

$$\beta = 1.04 + 0.173\frac{\mathrm{H}}{\mathrm{C}} + 0.043\frac{\mathrm{O}}{\mathrm{C}} + 0.248\frac{\mathrm{N}}{\mathrm{C}}\left(1 - 2.06\frac{\mathrm{H}}{\mathrm{C}}\right) \tag{2}$$

$$\mathrm{E^{CH}} = 1.08\mathrm{HHV} - 22.62\mathrm{H} - 0.86\mathrm{O} + 4.02\mathrm{N} \tag{3}$$

Subsequently, the fluidised bed gasification of OPEFB briquettes fuel was examined to investigate the effect of gasifier temperature, GT = 600 – 800 °C and Equivalence ratio, λ = 0.20 – 0.25. Gasification was examined under atmospheric pressure in an air driven allothermal bubbling fluidised bed gasifier using silica sand as bed materials. The gasifier schematic and ancillary components are presented in Figure 1. Details of the gasifier specifications are reported our previous gasifier design study (Johari et al., 2014).

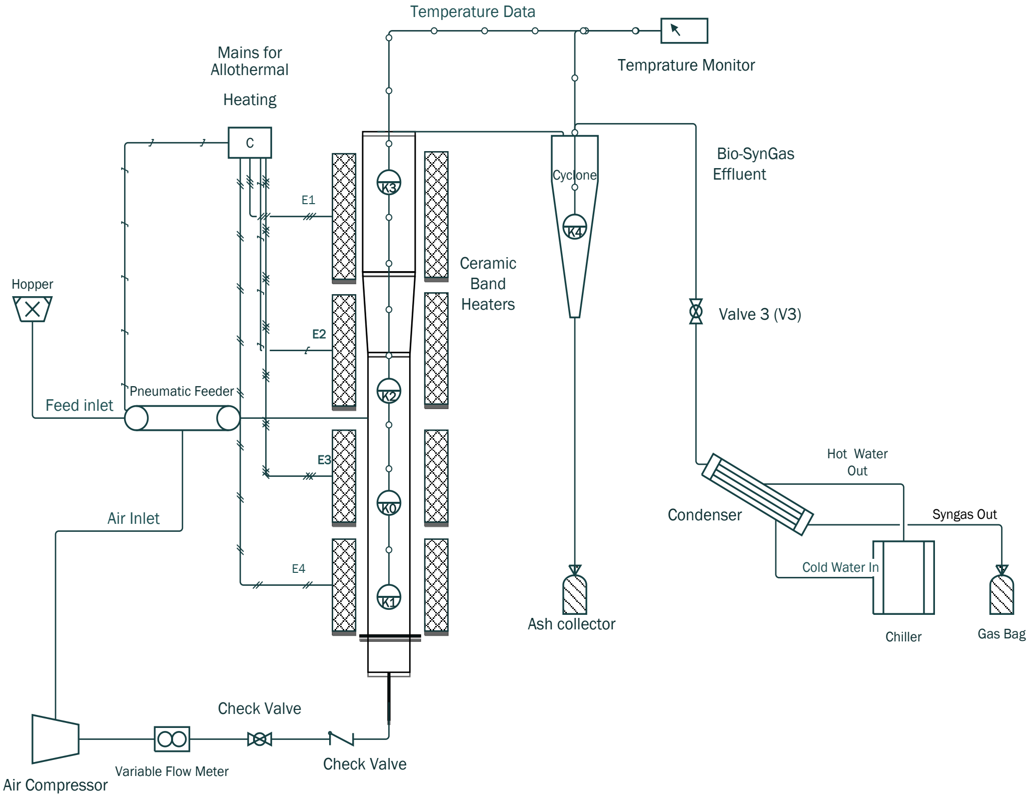

Figure 1: Schematic of fluidised bed gasifier for OPEFB gasification

During each run, the gasifier was loaded with 1,100 g of silica sand before heating the bed to 500 °C. Next, the fuel feeder and air blower were switched ON to load the OPEFB briquettes and air (at selected reaction equivalence ratio) into the gasifier at federate of 0.9 kg/h. The fluidising air triggered the high temperature mixing of OPEFB briquettes and bed materials producing the biosyngas and the fuel gas mixture. The effluent gas mixture was collected using Tedlar® gas sampling bags before gas chromatography analyses using the Agilent 6890N Network GC system equipped with thermal conductivity detector (TCD). The resulting gas peak areas representing H_2, CO, CO_2, CH_4 and hydrocarbons C_mH_n were deduced and the results computed to determine the compositions in mol%.

Based on the biosyngas and flue gas mixtures, the efficiency of the gasification process was examined based on the higher heating value (HHV, MJ/m^3), cold gas efficiency (CGE, %) and carbon conversion efficiency (CCE, %). The gasification efficiency parameters were deduced from the mathematical relations in Eqs(4), (5) and (6);

$$\mathrm{HHV} = (\mathrm{H_2}\ \% \times 30.52 + \mathrm{CO}\ \% \times 30.18 + \mathrm{CH_4}\ \% \times 95) \times 4.19\ \mathrm{MJ/m^3} \tag{4}$$

$$\mathrm{CGE}\ (\%) = \frac{\text{Heating Value of Product Gas}}{\text{Heating Value of Biomass}} \times 100\ \% \tag{5}$$

$$\mathrm{CCE}\ (\%) = \frac{\text{Carbon Content in Product Gas}}{\text{Carbon Content in Biomass}} \times 100\ \% \tag{6}$$

3. Results and Discussion

3.1 Chemical Fuel and Exergy Analysis

The chemical fuel and exergy analyses for OPEFB Briquettes are presented in Table 1.The results are compared with values typically observed for OPEFB* (Chew et al., 2016) and other biomass ** (Vassilev et al., 2015).

Table 1: Chemical Fuel and Exergy Analysis of OPEFB Briquettes

Element	Symbol	OPEFB Briquettes	OPEFB*	Biomass**
Carbon	C (wt%)	45.21	44.80	42.2 – 60.5
Hydrogen	H (wt%)	6.03	7.30	3.2 – 10.2
Nitrogen	N (wt%)	0.55	0.65	0.1 – 12.2
Sulphur	S (wt%)	0.21	0.47	0.01 – 1.69
Oxygen	O (wt%)	48.00	46.78	20.8 – 49.0
Moisture	M (wt%)	8.17	7.16	2.5 – 62.9
Volatiles	V (wt%)	71.83	68.58	30.4 – 79.7
Fixed Carbon	FC (wt%)	15.44	17.30	6.5 – 35.3
Ash	A (wt%)	4.56	6.96	5.0 – 48.9
Higher Heating Value	HHV (MJ/kg)	17.57	17.94	14 – 22.0
Lower Heating Value	LHV (MJ/kg)	16.34	16.62	13 – 20
Exergy (Eq(1))	E^{CH1} (MJ/kg)	18.17	-	-
Exergy (Eq(3))	E^{CH2} (MJ/kg)	17.17	-	-

The results indicate that OPEFB Briquettes contains sufficient proportions of chemical elements for energy fuels and power applications. The low concentrations of nitrogen and sulphur indicate OPEFB Briquettes is environmentally friendly with low potential for NOx and SOx emissions. Nevertheless, the high oxygen and ash contents may potentially pose operational challenges during gasification. The high ash content OPEFB is responsible for bed agglomeration (Lahijani and Zainal, 2011) and defluidisation (Lahijani and Zainal, 2014) during fluidised bed gasification.

The heating values of the fuel are higher than the minimum energy content (14 MJ/kg) required for bioenergy applications. The results indicate that HHV are lower than the values for coal an equally cheap, abundant and widely distributed alternative solid fuel globally utilised for power and energy applications (Vassilev et al., 2015). The exergy values ranged from 17.17 - 18.17 MJ/kg. This demonstrates that the maximum amount of work obtainable from the fuel per kg during conversion is below 20 MJ/kg (Bilgen, 2016).

3.2 Parametric Gasification

The parametric gasification of OPEFB Briquettes was examined under atmospheric pressure at gasifier temperatures, GT = 600 - 800 °C and Equivalence ratio, ER = 0.20 – 0.25 as presented in Table 2. The results presented indicate that fluidised bed gasification of OPEFB Briquettes yields biosyngas and flue gas mixtures comprising H_2, CO, CO_2, CH_4 and hydrocarbons C_2H_4 and C_2H_6.

Table 2: Biosyngas Composition of Gasified OPEFB Briquettes

Equivalence Ratio ER	Gasifier Temperature GT (°C)	Biosyngas Composition (mol%)					
		H_2	CO	CH_4	CO_2	C_2H_4	C_2H_6
0.20	600	10.17	4.08	3.10	16.78	2.04	1.04
0.20	700	4.33	3.08	1.83	16.25	1.67	0.43
0.20	800	2.02	3.66	1.08	14.06	1.49	0.49
0.23	600	4.19	2.22	1.55	21.01	2.20	0.91
0.23	700	4.35	2.58	1.10	22.67	2.34	0.65
0.23	800	4.90	3.29	1.36	27.29	2.19	1.18
0.25	600	4.35	3.20	1.73	13.70	1.49	0.73
0.25	700	3.11	6.27	1.06	10.88	1.00	0.38
0.25	800	4.21	2.94	1.89	14.26	1.31	0.81

The results indicate gasification of OPOEFB Briquettes under the selected conditions yielded H_2 gas ranging from 2.02 - 10.17 mol%; CO (2.22 - 6.27 mol%); CH_4 (1.06 - 3.10 mol%); CO_2 (10.88 - 27.29 mol%); C_2H_4 (1.00 - 2.34 mol%); and C_2H_6 (0.38 - 1.18 mol%). The highest yield of H_2 was observed at 600 °C whereas the lowest was observed at 800 °C both at ER = 0.20. This may be due to the limitation of heat and mass transfer typically observed in thermal conversion of biomass with large particle diameters (Lv et al., 2004). The study by Lv and co-workers observed that the evolution of biosyngas from large sized fuel particles during gasification was lower than smaller sized particles due to the dependence on mass and heat transfer. For small particles, the group observed that kinetics takes precedence as the reaction mechanism. Hence, gasification at low temperature and equivalence ratio is responsible for the H_2 content.

3.3 Gasification Performance

The OPEFB Briquettes gasification performance parameters; higher heating value (HHV, MJ/m^3), cold gas efficiency (CGE, %) and carbon conversion efficiency (CCE, %) are presented in Table 3. The HHV of the fuel ranged from 1.15 – 3.05 MJ/m^3 whereas the CGE was from 6.54 – 17.34 %. In general, the performance of the OPEFB Briquette gasification differs markedly from results for OPEFB (Lahijani and Zainal, 2011). This may be ascribed to the selected gasification parameters and fuel properties of the fuel. In spite of its excellent properties (low moisture, uniform solid shape and logistics), the large size of the fuel limits heat, mass transfer and hence the evolution of biosyngas and flue gases during gasification. Hence, smaller sized fuel particles, higher temperatures and lower ER values are recommended in future studies to ensure higher conversion efficiencies and biosyngas yields.

Table 3 Gasification Performance Analysis

Equivalence Ratio ER	Gasifier Temperature GT (°C)	Gasification Performance		
		Higher Heating Value (HHV, MJ/m^3)	Cold Gas Efficiency (CGE, %)	Carbon Conversion Efficiency (CCE, %)
0.20	600	3.05	17.34	59.85
0.20	700	1.67	9.50	51.48
0.20	800	1.15	6.54	46.00
0.23	600	1.43	8.16	61.76
0.23	700	1.32	7.50	64.96
0.23	800	1.58	9.02	78.16
0.25	600	1.65	9.38	46.16
0.25	700	1.61	9.18	43.37
0.25	800	1.66	9.45	46.96

The high biochar yield was observed during the gasification of OPEFB Briquettes as can be observed from the carbon conversion efficiencies (CCE) ranging from 43.37 – 78.16 %. The results indicate that higher temperatures and slower heating rates may be required to increase the conversion of OPEFB briquettes. Furthermore, the problems of bed agglomeration and defluidisation typically encountered in pulverised OPEFB were minimal during OPEFB briquettes gasification.

4. Conclusion

The fluidised bed gasification of OPEFB Briquettes, fuel properties and chemical exergy characterisation were examined in this study. The results indicated fluidised bed gasification of OPEFB briquettes produced sufficient quantities of biochar yield and biosyngas with heating values ranging from 1.15 – 3.05 MJ/m^3 whereas the CGE and CCE ranged from 6.54 – 17.34 % and 43.37 – 78.16 %, respectively. Bed agglomeration and defluidisation typically encountered in un-pelletised OPEFB were minimal during briquettes gasification. In conclusion, the results demonstrated that OPEFB Briquettes gasification is a practical route for valorising OPW into renewable energy and sustainable fuels for the future.

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