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On Gasification of Different Tropical Plant-based Biomass Materials

Shaharin A. Sulaiman, Muhammad F. Karim, M. Nazmi, Z. Moni and Samson M. Atnaw
Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 31750 Tronoh, Perak, Malaysia

Corresponding Author: Shaharin A. Sulaiman, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 31750, Tronoh, Perak, Malaysia

ABSTRACT

In this study, the characteristics of synthetic gases derived from different plant-based biomass feedstocks are studied using a downdraft gasifier. The biomass materials are oil palm frond, mangrove wood, sugarcane bagasse and coconut husk. Understanding of these characteristics would lead to proper judgment on the suitability of co-gasification of the different biomass materials. The temperature profiles in the gasifier are recorded and the syngas compositions are estimated. It is found that the mangrove wood has the highest energy content (22,292 J g^{-1}) at 11% moisture content (wet basis). It is also observed that mangrove wood has nearly similar properties to that of oil palm fronds as compared to sugarcane bagasse and coconut husks.

Key words: Biomass, downdraft gasification, syngas

INTRODUCTION

The demand for fossil fuels increases rapidly and the amount of energy consumption is estimated to reach 100 million Tons of oil equivalent by 2030 (Shuit *et al.*, 2009). Biomass can exist as a sustainable source of non-conventional energy to reduce the dependence on fossil fuels. For energy generation, plant based material is often used, although animal derived biomass material may also be used. Chemically, biomass is carbon based. It is composed of organic molecules containing hydrogen, oxygen and nitrogen and also traces of other atoms like alkali and heavy metals.

Thermal conversion of biomass via gasification is achieved in the presence of heat (between 700 and 1000°C) and oxygen of limited supply. The result of such an incomplete combustion is a synthetic gas or syngas consisting of mainly carbon monoxide (CO), Nitrogen (N_2), Hydrogen (H_2) and traces of methane (CH_4) (Rajvanshi, 1986; Atnaw *et al.*, 2011a; Kumar *et al.*, 2008). A typical simplified gasification reaction is given by:

$$CH_{1.4}O_{0.6}+0.2O_2\rightarrow CO+0.7H_2 \tag{1}$$

The resulting syngas from gasification can be utilized in several applications. One of the most attractive uses of producer gas is its use in internal combustion engines for the production of mechanical power in electricity generation, automotive engine, water pumping, rice milling, compressor operation, etc. In addition, syngas can also be directly combusted in external combustion systems such as boilers, kilns, driers, ovens etc. Despite the potential, there is some setback in the present gasification technology, in which there is not a single universal gasifier that is capable to handle all types of biomass materials. This is because biomass exists in a wide variety of forms and thus making it necessary to tailor the shapes of the gasifier to each form (Rajvanshi, 1986). The synthesis gas is affected by the various processes involved; i.e., drying, pyrolysis, combustion and reduction. Furthermore, variation in the gases produced from different biomass sources is expected due to their different chemical compositions. The Higher Heating Values (HHV) of common plant-based biomass sources range between 5 and 20 MJ kg^{-1} (Arbon, 2002; Quaak *et al.*, 1999) of which the range of values is considered wide. On an average 1 kg of biomass produces around 2.5 m^3 of syngas at standard temperature and pressure (Rajvanshi, 1986). About 1.5 m^3 of air is consumed for combustion in gasification (Schapfer and Tobler, 1937) as compared to about 4.5 m^3 of air for direct combustion (at stoichiometric) of wood. In other word, biomass gasification consumes about one third of the theoretical air-fuel ratio required for stoichiometric wood burning.

Although, one design of gasifier may not be suitable for all types of biomass source, it would be beneficial if the source of biomass can be diversified to overcome inconsistency or interruption in the operation of gasifier that can be caused by discontinuity due to seasonality of feedstock. Therefore, a study is required to determine the suitability of co-gasifying different biomass sources. The objective of this work is to assess the thermochemical and gasification properties of different biomass prior to exploring into the feasibility of co-gasification in a common gasifier.

MATERIALS AND METHODS

The thermochemical properties of the biomass feedstock were measured through various standard tests. Gasification of the feedstock materials were performed in a downdraft gasifier. A computer simulation was done to predict the gas composition and its calorific value. Four types of biomass were harvested from locations surrounding the state of Perak in Malaysia. They were oil palm fronds, Rhizophocea (mangrove tree) woods, sugarcane bagasse and coconut husks. Oil palm fronds and woods samples were cut to a size of 1-2 inch while the bagasse and coconut husks were not cut because of their broom like extremities. The feedstock were left to dry under the sun for a period of 1 week. The dried feedstock then underwent grinding using a granulator. The granulated samples were then turned into powder using a rock lab grinder. The fine powder form of sample would be used in calorific value, ultimate and proximate analysis. The study is done experimentally and also with the use of a simulation software, for oil palm frond, mangrove wood, sugarcane bagasse and coconut husk.

Measurements of thermochemical properties: The thermochemical property tests include the ultimate analysis, proximate analysis and calorific value measurement. For ultimate analysis, the powdered OPF was analyzed using the Leco CHNS-932 analyzer in accordance with ASTM D3176-89(2002) (ASTM, 2002) to determine its carbon, hydrogen, nitrogen and sulphur contents. The chemical composition of a biomass sample helps to determine whether it is suitable for gasification. For instance, a low content of sulphur is desirable, as its emission could react with water, oxygen and oxidants to form acidic compound such as acid rain. On the other hand, high carbon content is preferred as it is an important element in the fuel for the gasification process.

The proximate analysis was performed to express the burning characteristics of the biomass, comprising Fixed Carbon (FC), Ash, Moisture and Volatile Matter (VM), by using the Perkin Elmer TGA7 Analyzer at an operating temperature range of between the room temperature to 900°C with an accuracy of ±2°C. The tests were conducted in accordance to ASTM E 1131-98, Standard Test Method for Compositional Analysis by Thermogravimetry (ASTM, 2004).

The calorific value of a biomass fuel is critical in choosing an appropriate technology for energy conversion. In the present work, the calorific value of the biomass samples was determined using IKA C-5000 bomb calorimeter in accordance to ASTM D 5865-07, Standard Test Method for Gross Calorific Value of Coal and Coke (ASTM, 2007). In the measurements, the gross calorific value of the specimen was defined as the heat released by a complete combustion of a unit quantity, at a constant volume, in an oxygen bomb calorimeter under standard conditions. Six measurements were conducted for the calorific value tests and five for the Ultimate Analysis. Three measurements were conducted for each of the Proximate Analysis test. The values were averaged and the standard deviations were calculated.

Computer simulation: Prediction of the composition of the resulting syngas from gasification of biomass was conducted by computer using Engineering Equation Solver (EES). The simulation program was developed by Fock *et al.* (2000). The desired outcomes of the simulations in this study were synthesis gas compositions and calorific values of the resulting synthesis gases. Detailed descriptions of the program were reported elsewhere (Moni and Sulaiman, 2010).

Gasification experiment: The downdraft gasifier, which had a thermal power output of 50 kW, was assembled as shown in Fig. 1 and the experiment was conducted using a downdraft gasifier with atmospheric air used as gasification media. A cyclone unit was attached in order to have a cleaner syngas emission. The air was supplied using a Shanghai Ken Tools Vortex blower model Ken 4210 and the air flow rate was controlled using conventional ball valves. Water-based manometers were attached to air inlet pipe MM01, reactor body MM02 and exhaust pipe MM03 for determination of the flow rate of the air intake. Syngas combustibility was tested using a handheld butane torch at the top of the funnel. Details of the design and operation of the gasifier can be found in the reference (Moni and Sulaiman, 2008; Sulaiman *et al.*, 2011; Atnaw *et al.*, 2011b). Up to six type-N thermocouples were connected into the gasifier reactor in order to record the temperature of each reactor zone during gasification. One type-K portable thermocouple was connected to the flare tip and outlet to determine the respective temperature values. All type-N thermocouples were connected to a desktop computer via a USB data logger for continuous monitoring and recording purposes. The fuel bed was provided with a perforated grate to pass the ash while supporting the char and unreacted feedstock during the process. At the end the gasification run the ash would be collected from the ash box blow the grate.

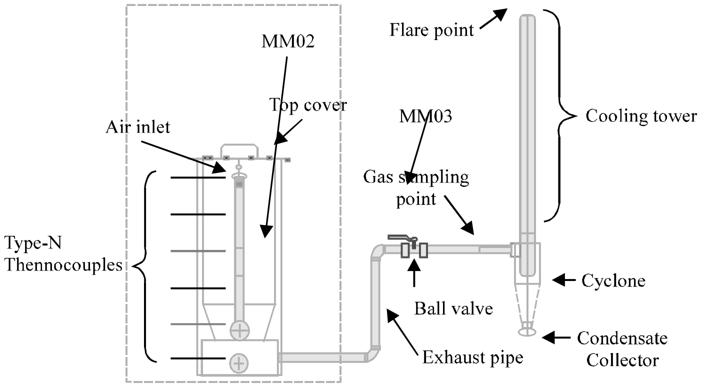

Fig. 1: Schematic of the downdraft gasification system

RESULTS AND DISCUSSION

Thermochemical properties: Table 1 is the average measured energy content of the biomass samples. Clearly mangrove woods (Rhizophocea) is shown to contain the highest calorific value at 22,292 kJ kg^{-1}. The next highest calorific value is found in sugarcane bagasse at 18,838 kJ kg^{-1}, of which the value is close to that of oil palm fronds and thus suggesting that the two materials have a potential to replace each other in gasification operations. The measured values of the four biomass materials were found to be comparable to that for different biomass sources (Ganan *et al*., 2006; McKendry, 2002).

Table 2 shows the average measured composition of carbon, hydrogen, nitrogen and sulphur of the biomass samples in weight percentage on dry basis, as obtained from the ultimate analysis. It is shown in Table 2 that mangrove woods have the highest carbon content and coconut husks have the least. Nevertheless, the carbon contents for mangrove wood, oil palm fronds and sugarcane bagasse are shown to be close to each other, implying a common property. This show the potential and comparability of OPF as energy fuel, as well as for use in co-gasification with mangrove wood and sugarcane biomass. The sulfur contents of all the biomass samples are shown to be excellent; i.e. lower than 0.1%. With regard to hydrogen content, sugarcane bagasse has the lowest content. It is also interesting to note that mangrove wood has the smallest and significantly low nitrogen content at 0.034%. The H:C ratios for the biomass samples range between 0.12 and 0.17. The results for proximate analysis are shown in Table 3. The moisture content of the feedstocks was found to be below 25%, signifying their suitability for thermal conversion applications such as gasification. The moisture content for sugarcane bagasse was shown to be significantly high at about 21% as compared to other samples of which their moisture contents are lower than 12%. The volatile matter was found to be the highest for sugarcane bagasse at 65.3%, whereas mangrove woods displayed a significantly low value of about 40.6%. Sugarcane bagasse has the lowest value of fixed carbon at 11.35% while coconut husks have the highest value at

Table 1: Energy analysis of each type of feedstock

Biomass type	Average HHV (kJ kg^{-1})
Oil palm fronds	18,184
Mangrove woods	22,292
Sugarcane bagasse	18,838
Coconut husks	16,863

Table 2: Ultimate analysis of each feedstock (wt. %)

Biomass type	C	H	N	S
Oil palm fronds	48.430	8.316	0.339	0.024
Mangrove woods	52.090	8.093	0.034	0.073
Sugarcane bagasse	45.780	5.425	0.197	0.072
Coconut husks	39.490	6.068	0.399	0.064

Table 3: Proximate analysis of each feedstock (wt. %)

Biomass type	Moisture content	Volatile matter	Fixed carbon	Ash content
Oil palm fronds	5.33	54.05	33.64	6.96
Mangrove woods	11.00	40.55	40.46	8.00
Sugarcane bagasse	20.67	65.30	11.35	2.69
Coconut husks	6.67	48.13	40.73	4.47

40.73%. As for ash content, a value of below 12% would be desired in order to avoid the occurrence of slagging and in Table 3 all the biomass materials are shown to be within a satisfactory range.

Observations from gasification: The total duration of gasification operation to consume a batch of feedstock was over 60 min. Figure 2 shows the variation of temperatures in the gasifier reactor with time from the start of process for Oil Palm Fronds (OPF). In general, the maximum temperature of the combustion zone reached 800°C. The maximum flue gas temperature was recorded at 313°C. The syngas could be ignited and able to intermittently sustain yellowish and orange flares for 2 to 3 min. With OPF, almost no liquefied tar or condensates were found inside the condensate collector, mainly due to the high exhaust temperature; i.e., larger than 150°C. The intake air flow rate was at an average of 0.025 m^3 sec^{-1}.

Figure 3 shows the variation of temperatures in the gasifier reactor with time from the start of process for mangrove woods (Rhizophocea), of which the setup was slightly different whereby a gas sampling train was attached to collect the syngas for composition analysis. Overall, the gasification was a success as flare can be lit up and sustained for 4 to 5 min. There was no bridging problem and tar for formation was not detected. However, the average temperature in the combustion zone was low at 600°C. This value is relatively lower than that observed for OPF. The maximum

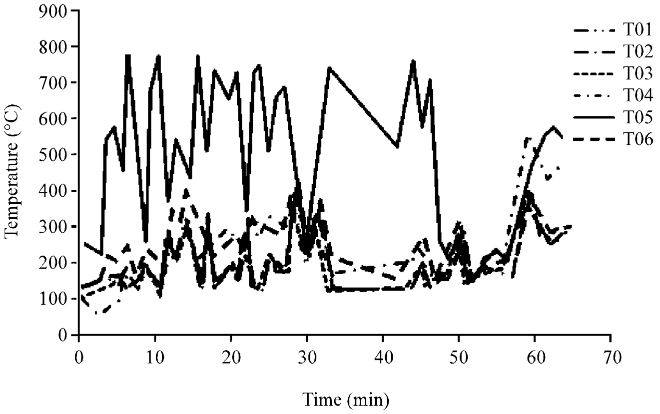

Fig. 2: Schematic of the downdraft gasification system

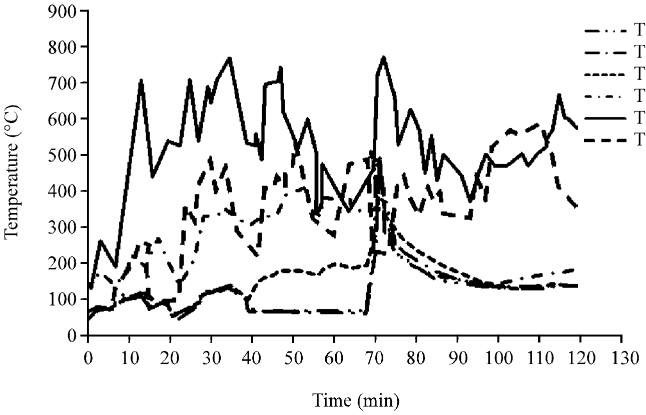

Fig. 3: Temperature variation of OPF gasification with time

temperature of the flare gas was recorded at 407°C. Yellowish and orange flares were produced with no traces of blue flame. The intake air flow rate was recorded at an average of 0.034 m^3 sec^{-1}. The syngas was collected using a gas bag and gas chromatography analysis was performed and the results are shown in Table 4. It is shown from the test that hydrogen constitutes the highest percentage in the resulting syngas at 51.7% while methane constitutes the lowest percentage at 2.5%.

Figure 4 shows the variation of temperatures in the gasifier reactor with time from the start of process for sugarcane bagasse is shown. In the experiment, it was observed that initially no combustible syngas could be detected. This could probably be the result of uneven distribution of the feedstock inside the gasifier or due to high moisture content of the bagasse. Besides, there seemed to be a bridging problem whereby the sugarcane bagasse was found stuck in the drying zone and pyrolysis zone, possibly contributed by the broom-like extremities and fibrous physical properties of the biomass material. Syngas was later produced after solving the bridging problem by opening the hopper and stirring the feedstock. Despite the initial problems, sugarcane bagasse produced a larger and more stable flare than OPF. The temperature of the combustion zone occasionally exceeded 1000°C. However, the tar formation was quite severe. Furthermore, the frequency of the bridging problem was high that the hopper had to be opened several times to stir the feedstock. The maximum flare gas temperature was recorded at 480°C. Yellowish and orange flares were able to be sustained for 3 to 4 min. The intake air flow rate was recorded at an average of 0.042 m^3 sec^{-1}.

Figure 5 shows the variation of temperatures in the gasifier reactor with time from the start of process for coconut husks. Overall, the gasification produced combustible syngas, in which the flare could be sustained intermittently for 4 to 5 min. However, through observation the number of times that the output gas can be flared decreased as compared to other biomass materials. Tar was also

Table 4: Gas chromatography result for syngas derived from mangrove woods

Chemical composition	GC analysis results (ppm)	Overall composition (%)	Relative composition (%)
CO_2	13,715	1.4	32.0
CH_4	1,053	0.1	2.5
CO	5,944	0.6	13.9
H_2	22,158	2.2	51.7

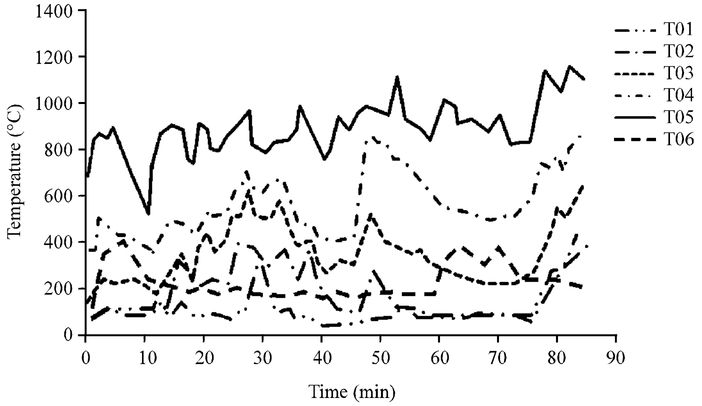

Fig. 4: Temperature variation of sugarcane bagasse gasification with time

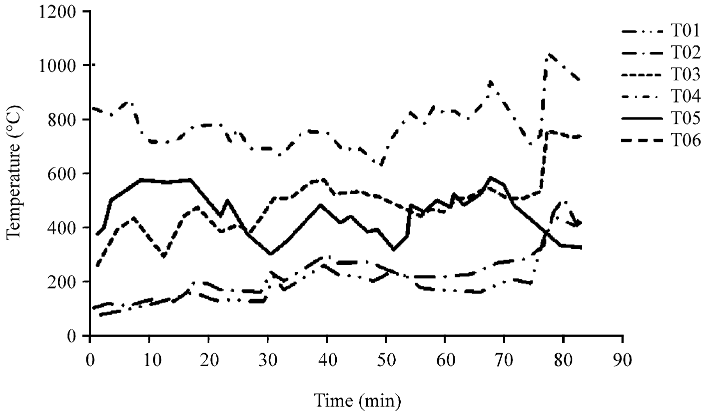

Fig. 5: Temperature variation of coconut husks gasification with time

Table 5: Composition of syngas from Engineering Equation Solver (EES) and gas chromatograph analysis

Biomass type	CO	H_2	CO_2	CH_4
OPF (EES)	23.69	37.71	35.03	3.57
Sugarcane bagasse (EES)	24.77	28.25	44.89	2.09
Mangrove woods (GC)	13.87	51.69	31.98	2.46
Coconut husks (EES)	22.94	32.74	36.74	7.58

found around the gasifier and during experiment. The flow rate of air in the pipe was also observed to be inconsistent and this was probably due to clogging or blockage in the pipe due to the presence of tar. Due to inconsistency, the air flow rate was varied a few times in order to achieve combustible syngas. The maximum flare temperature was low at 202.3°C and the outlet temperature was 165.7°C. Table 5 shows the simulation results from the EES program and also the Gas Chromatography analysis. Only the syngas resulted from gasification of mangrove woods were tested with Gas Chromatography due to limited access to the equipment, which did not belong to the authors' research group. Technically, the syngas contain two major gases, which are carbon monoxide and hydrogen. From the results in Table 5, it is obvious that in all of the biomass materials, the two major gases form more than 50% of the total syngas composition (61.4% for OPF, 53.0% for sugarcane bagasse, 65.6% for mangrove woods and 55.7% for coconut husks). The percentages of methane for all the biomass are shown to be small at an average value of 3.9%. Beside the four gases, there are other impurities such as nitrogen compound and tar that are not being presented simply because of the limitation of the simulation model. In the EES program simulation, only these four major elements were being considered.

CONCLUSIONS

Initial physical and chemical properties as well as characteristics of synthetic gases derived from four different biomass materials were studied. The biomass materials studied include oil palm fronds, mangrove wood, sugar cane bagasse and coconut husk. The chemical properties and initial calorific values of the biomass materials as well as results of gasification experiment showed that mangrove woods and oil palm fronds could suitably replace each other as gasification feedstock. In the gasification of both mangrove woods and oil palm fronds a stable syngas was obtained with minimal tar formation observed. Whereas, during gasification of sugar cane bagasse, bridging problem was evident possibly due to fibrous nature and its broom-like extremities. Such fibrous nature causes entanglement of the feedstock blocking the continuous flow of material in the gasifier bed. During gasification of coconut shells and husks, blockage of gas outlet pipe due to slagging as well as severe tar formation was observed. In addition, comparable composition of syngas (CO, CO_2, CH_4, H_2) was found for oil palm fronds and sugarcane biomass.

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