GASIFICATION PERFORMANCE OF SUB-BITUMINOUS COAL WITH SAWDUST AND SAWDUST PELLET

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Abstract

Utilisation of fossil fuel and biomass for power generation systems aids in minimising CO_2 emission and fossil fuel consumption, resulting in clean energy. The purpose of this study was to investigate the gasification performance of sub-bituminous coal (CL) with raw biomass; sawdust (SD) and pelletised biomass; sawdust pellet (SDP). Gasification was carried out in a lab-scale air-blown downdraft gasifier at a 1:1 mass ratio of CL with SD and SDP at a fixed condition of gasification temperature at 750 °C and equivalence ratio (ER) of 0.25. The gasification output was analysed in terms of syngas composition: hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH4), and the gasification performance: the calorific value of the syngas (CV_{syngas}), gasification efficiency (X_{GE}) and carbon conversion efficiency (X_{CC}). It was found out that CL/SDP produces high syngas composition than CL/SD, with a difference of 20%, 22%, 33% and 60% for H_2, CO, CH_4 and CO_2, respectively. In addition, the CL/SDP outperformed the gasification performance for the CV_{syngas}, X_{GE} and X_{CC} at 4.958 MJ/Nm^{3,} 25% and 34%, respectively. Therefore, this study provides the preliminary investigation into mixing the pelletised biomass with fossil fuel to improve the syngas composition and gasification performance while also tackling the biomass limitations.

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Faculty of Civil Engineering Technology, UMP Research Series: Water, Energy, and Environment, Vol. 1, [insert doi here later]

Keywords downdraft gasification, syngas, biomass, pelletised biomass.

Introduction

Biomass gasification appears to be an appealing technology to produce an energy-rich gaseous product that can be utilised to generate greener power than direct combustion (Mallick et al., 2018). Biomass itself is reported to have a large amount of volatile matter and high H/C tends to enhance the calorific value, thus improving the gasification efficiency (Wang et al., 2013). The gasification process transforms biomass into a combustible gas mixture; the synthesis gas in a low oxygen content environment at a high temperature typically ranges 650-1200°C (Wasinarom & Charoensuk 2019). Even though sawdust is an abundant by-product that has been agreed upon its potential for the gasification process (Chen et al., 2015; Mansur et al., 2020), however, it has a low energy density and is challenging to handle, leading to an adverse effect on the collection and transportation cost. Thus, pre-treated fuels are necessary to overcome the biomass constraints for the production of biofuels. Pre-treatment refers to the intermediate phase accomplished on the biomass sources before being consumed for the final conversion, as the biomass is altered physically or chemically for a greater utilisation in the fuel field (Stapf et al., 2019). The pretreatment procedures are divided into thermal treatment (drying, torrefaction), mechanical treatment (size reduction, grinding, densification), and biological treatment (washing/leaching) (Yang & Kumar, 2018). Gasification of pellet fuel results in significantly more stable syngas composition, and the gasification performance is quite steady and efficient (Kumar et al., 2017). This is because the pellet features a uniform structure and compact density that facilitate the handling and feeding process, by preventing the bridging within the gasifier reactor and improving the gasification reactions (Yoon et al., 2012).

Co-gasification is the process of mixing two or more biofuels and converting them into a gaseous product that can be utilised later to generate electricity, hydrogen, chemicals and liquid transportation fuels (Edreis et al., 2020; Mallick et al., 2017). Biomass reduces the environmental impact as it is a carbon neutral source when mixed with coal in the co-gasification process. This method employs carbon sequestration technology, resulting in a carbon-negative process as carbon is used. Moreover, char conversion is elevated, owing to the synergy effect of coal and biomass rather than on the coal alone, leading to low efficiency and high carbon discharge (Yan & He, 2017). Various technologies are available nowadays to gasify coal and biomass; nevertheless, there are some uncertain matters, particularly how to blend them to yield high gas output. For that reason, several questions have been raised about this co-gasification, such as the effect of feedstock quality on the output's quality, the optimum amount of coal with biomass blends, and the geographical aspects of coal and biomass co-gasification (Sbusiso, 2014). Moreover, in economic benefits, co-gasification technology on biomass and fossil fuels offer several advantages, including the ability to combine the utilisation of reliable coal supply with biomass, by qualifying for renewable commitment and climate change benefits. Thus, the co-gasification of fossil fuels together with biomass has gained the interest of researchers. To the author's knowledge, while numerous co-gasification tests have been carried out using the biomass-coal mix, the proposed comparison between coal with raw biomass and pelletised biomass has yet to be investigated.

This study focuses on investigating the gasification of the 50% sub-bituminous coal (CL) with raw biomass (sawdust, SD) and pelletised biomass (sawdust pellet, SDP), employing an air-blown fixed-bed downdraft gasifier. The composition of the gaseous product and the performance of the gasification process were assessed. The heating value of the syngas (CV_{syngas}), gasification efficiency (X_{GE}) and carbon conversion efficiency (X_{CC}) were evaluated as gasification performance.

Material and Methods

Feedstock Material and Characterization

Sawdust (SD) is a by-product acquired from a wood factory located in the north of Malaysia, Penang. The dried powdered SD is pelletised using the extruder pellet machine to produce the sawdust pellet (SDP). The produce SDP adopted an air cooling technique for cooling purposes before being manufactured. Meanwhile, the sub-bituminous coal (CL) is collected from the electricity utility company in Malaysia via a third party. Figure 1 displays the image of each of the samples utilised in this study. The samples were then manually mixed at a 1:1 ratio of CL to SD and SDP. The mixture samples were stored in an air-tight container to prevent any additional moisture. The proximate analysis was analysed according to ASTME1131 (ASTM E1131-98, 1998); whereas the ultimate analysis followed ASTM D3176 (ASTM D3176-09, 2009). Furthermore, each sample's heating value was measured using the bomb calorimeter (IKA C200).

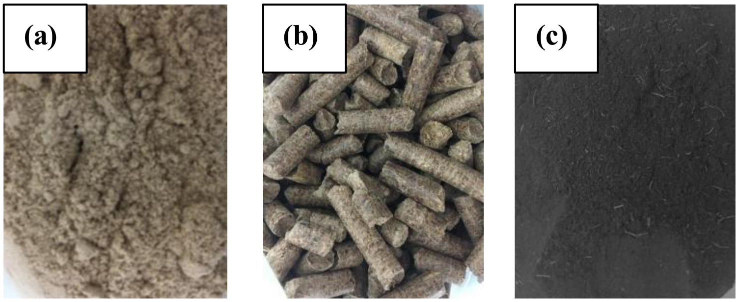

Figure 1: The image of the SD, SDP and CL.

Gasification Experiment

Figure 2 depicts the experimental rig used in the biomass laboratory, located at Universiti Teknologi Petronas (UTP), Perak, at the Department of Mechanical Engineering. The experimental rig, which is the gasification system, has three major components: the gasifier reactor, the gas cleaning and the gas analyser. An electric furnace heated the reactor with a height of 500mm and an inner diameter of 80mm. Furthermore, to minimise the heat loss, the reactor was encased with 50mm thickness of the ceramic fibre. The compressed air equipped at the bottom side connected to the rotameter functioned to supply the air directly to the top of the gasifier and control the airflow rate. Meanwhile, the residual solids produced were collected at the reactor's bottom end, attached to the gas discharge hole.

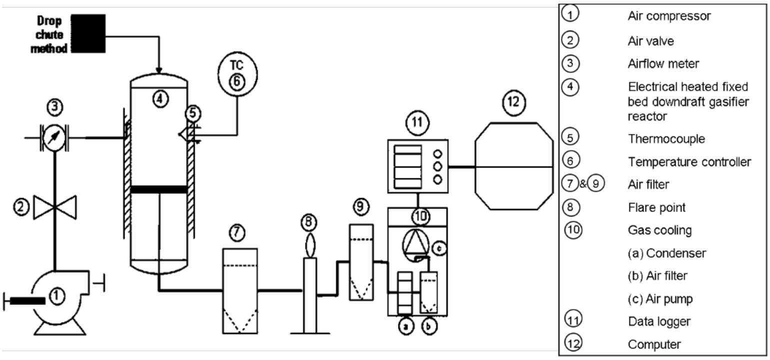

Figure 2: The schematic diagram of the air-blown lab-scale downdraft fixed bed gasification system.

Once the system is switched, the air is flushed into the reactor at the regulated desired temperature for 5-10 minutes to maintain a stable state before running the experiment. Once the stable state is achieved, the gasification flow rate at 3 L/min was set to keep the equivalence ratio (ER) at 0.25 based on the energy balance stoichiometric of oxygen (O_2) in a self-sufficient autothermic process. The drop-chute method was applied to feed 100 g of samples into the top of the gasifier reactor. Subsequently, the temperature of the gasification process was set to 750 °C, as it is the optimal temperature based on the initial experiment run. The produced syngas was then routed to the gas analyser passing through the gas cleaning and cooling system. The syngas composition was recorded and collected using the data logger equipped in the computer. After a run, the remaining solid from the cooled reactor was collected and weighed.

The effects of gasifying the 1:1 ratio of CL with SD and SDP on the syngas composition (H_2, CO, CH_4 and CO_2), and gasification performance were examined. The heating value of the syngas (CV_{syngas}), gasification efficiency (X_{GE}) and carbon conversion efficiency (X_{CCE}) were used to evaluate the gasification performance. The CV_{syngas} (MJ/Nm^3) referred to the quality of syngas composition with regards to energy content per fixed volume or mass from the gasification process and computed by factoring the volume percentage of combustible gas components in the syngas (CO, H_2 and CH_4) with their specific heating value following the US National Renewable Energy Laboratory (NREL), as expressed in the Equation (1) (Basu, 2010).

$$CV_{syngas} = (V_{CO} \times 12.63) + (V_{CH_4} \times 39.82) + (V_{H_2} \times 12.74) \qquad (1)$$

Where V is the volumetric percentage for CO, CH_4 and H_2 derived from online gas analyser data. Furthermore, the gasification efficiency (X_{GE}) is computed by taking into consideration the CV_{syngas} divided by the energy content of the biomass (Shi, 2016), calculated as the following Equation (2).

$$X_{GE} = \frac{CV_{syngas}}{CV_{fuel}} \times 100 \qquad (2)$$

Where CV_{syngas} refers to the value of the syngas (MJ/Nm^3) and CV_{fuel} represents the heating value of the sample (MJ/kg). Furthermore, the carbon conversion efficiency (X_{CC}) was defined as the ratio of carbon atoms to input carbon atoms in the samples (Nam et al., 2016). The X_{CC}, Equation (3) was described as follows: (Rodrigues et al., 2017).

$$X_{CC} = \frac{12 \times A}{m_{fuel} \times x_C} \times 100 \qquad (3)$$

Where A is the total number of moles of carbon-bearing components (CO, CH_4 and CO_2) of the syngas produced; m_{fuel} is the mass of fuel (100g); and x_c is the carbon's mass fraction for SD and SDP.

Result and Discussion

Feedstock Characteristics

The proximate, ultimate, O/C ratio, H/C ratio and heating value of the sample mixture are shown in Table 1. The moisture content in CL/SDP (9.32 %) was predicted to decline from 10.92 % (CL/SD) after the thermal pre-treatment process in pelletisation, considering the mechanical force applied during the production process (Tumuluru et al., 2012). Meanwhile, it has been discovered that the CL/SDP contains a high amount of volatile matter (VM) compared to the CL/SD. This could be because the higher ash content in CL contributed to the numerous catalytic components in the ash added to the SDP, resulting in the char gasification within the gasification process (Mueller et al., 2015). As a result, mixing the pelletised sawdust and coal makes the sample easier to be ignited than raw biomass and coal alone, consequently improving the gasification performance.

The ultimate analysis of the samples was identical to each other with an average of 3% when mixing the CL with SDP. The average value of H/C and O/C ratios of the samples were determined to represent the relationship between the heating value of the samples and the atomic ratio of (H/C) and (O/C) (Basu, 2010). It is emphasised that increasing the (H/C) and (O/C) results in a greater heating value of the syngas. Table 1 also demonstrates that CL/SDP has a higher heating value than CL/SD, based on the high amount of (H/C) and (O/C) ratio. Sukiran et al. (2011) also stated that the atomic ratio (H/C) and the (O/C) represent the combustible hydrocarbon features for fuels. As CL/SD recorded lower H/C and O/C values, it can be expected that CL/SD have a lower gasification efficiency than CL/SDP. The elemental composition of the samples reveals that CL/SDP is ecologically friendly, as it is projected to yield a minimal amount of N_2 and S. The sample's heating value is crucial for calculating the thermal efficiency of the gasifier for syngas generation, as presented in Table 1. It can be indicated that the heating value of CL/SDP is substantially higher than CL/SD, with the amount of 18.28 MJ/kg. Pelletised sawdust resulting in pretreatment will enhance the sample's characteristics by making it uniform and reducing its moisture content, hence improving the heating value (Sahraei-Nezhad & Akhlaghi-Boozani, 2010). Thus, it can be inferred that the mixture of CL with SDP tends to exceed the later gasification performance of using CL and SD.

Table 1: The proximate, ultimate, O/C ratio, H/C ratio and heating value of 50% ratio of CL with SD and SDP.

	CL/SD	CL/SDP
Proximate analysis (wt. %)		
Moisture content (MC)	10.92 ± 0.78	9.32 ± 0.23
Volatile matter (VM)	48.23 ± 0.80	79.13 ± 0.44
Fixed carbon*(FC)	38.41 ± 0.63	8.83 ± 0.78
Ash content (AC)	2.44 ± 0.81	2.72 ± 0.70
Ultimate analysis (wt. %)		
Carbon (C)	48.35	48.43
Hydrogen (H)	5.71	5.83
Nitrogen (N)	1.82	1.27
Oxygen (O)*	42.21	43.76
Sulphur (S)	1.92	0.71
H/C ratio	1.42	1.44
O/C ratio	0.65	0.68
Heating value, CV_{fuel} (MJ/kg)	18.04 ± 0.21	18.28 ± 0.64

**By difference, O% = 100- (C%-H%-N%-S %)*

Syngas composition

Figure 3 displays the syngas composition of H_2, CO, CH_4 and CO_2 for 50% of CL with SD and SDP under gasifier operating conditions of 750 °C and ER at 0.25. In general, CL/SDP possessed higher syngas composition than CL/SD. For the CL/SD, the volume of the H_2 is less than CL/SDP, probably due to a higher fraction of the atomic hydrogen in raw biomass being converted to H_2O (Chen et al., 2013). When pelletised sawdust is gasified, the H_2 content rises dramatically to 17%. These findings showed that the pelletisation process is capable of enhancing syngas production parallel with the findings of Aydin et al. (2019). Higher CO_2 levels in the CL/SDP could be due to some CO molecules being oxidised to CO_2 during the water-gas-shift process (Meng et al., 2019). Moreover, CH_4 recorded the lower amount of syngas composition, averaging 5% opposing for methanol synthesis.

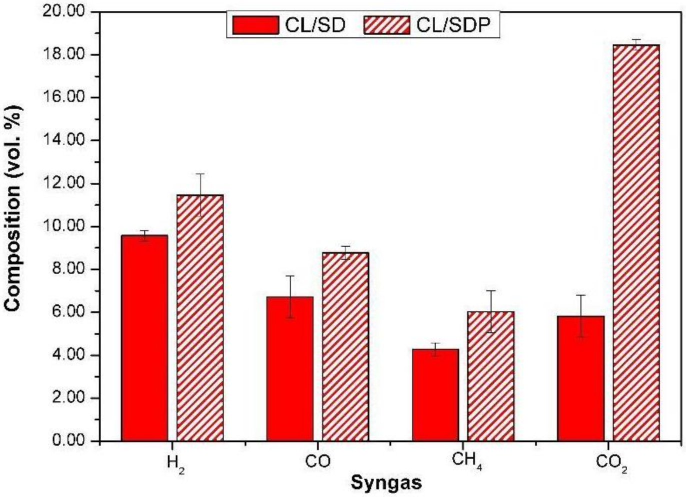

Figure 3: The syngas composition for 50% of CL with SD and SDP fixed at 750 °C and 0.25.

Gasification performance

Figure 4 illustrates the CV_{syngas}, X_{GE} and X_{CC} for the mixture of CL with SD and SDP. It can be seen that the mixture of CL/SDP achieved higher CV_{syngas}, X_{GE} and X_{CC} than CL/SD. The value of the CV_{syngas} has boosted an average 23%; with the CV_{syngas} for CL/SD and CL/SDP computed at 3.771 ± 0.23 MJ/Nm^{3}and 4.958 ± 0.34 MJ/Nm^3, respectively. In addition, the difference of X_{CC} for CL/SD and CL/SDP is typically 60%, in which the X_{CC} for CL/SDP is measured at 34.34 ± 0.22%. The pelletisation process aids in removing the moisture content due to the mechanical force, eventually yielding higher H_2 in syngas composition, with the addition of CL elevated the value of the CV_{syngas} and X_{GE}. It should be pointed out even though the X_{CC} denoted the amount of carbon being converted to the hydrocarbon gaseous; the value does not represent the better gasification performance. Despite that, CL/SDP still achieved the higher X_{CC} that increased by 20% from CL/SD. Increases of X_{cc} for the pelletised biofuels are consistent with those of Yoon et al. (2012).

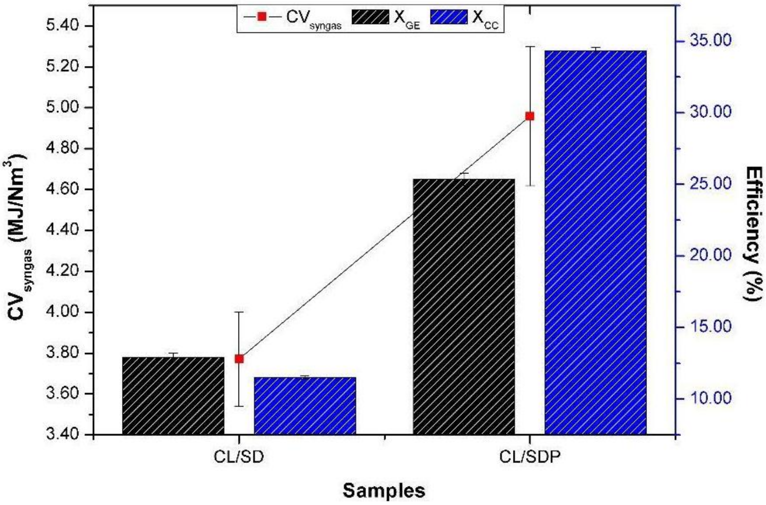

Figure 4: CV_{syngas}, X_{GE} and X_{CC} for 50% of CL with SD and SDP at the fixed condition of 750 °C and 0.25.

Conclusion

The effect of 50% of CL with SD and SDP in the fixed bed air-blown downdraft gasifier at the fixed gasification temperature and ER of 750 °C and 0.25, respectively, on the syngas composition and gasification performance, was examined. The addition of 50% CL to the SDP led to the significant syngas generation of H_2 and CO at 11% and 9%, respectively. CL/SD, on the other hand, had low H_2 and CO yields, at 9% and 8%, respectively. Meanwhile, the gasification performance followed a similar pattern, in which CL/SDP achieved high CV_{syngas}, X_{GE} and X_{CC} computed at 4.958 MJ/Nm^3, 25%, and 34%, respectively. The above results suggest that pre-treated SD into SDP with the addition of CL improves the gasification efficiency rather than using the SD and attempts to address the biomass constraint in biofuels production.

Acknowledgement

This project was funded by the Ministry of Higher Education Malaysia and Universiti Malaysia Pahang through the FRGS/1/2014/TK06/UMP/02/6 and PGRS190394, respectively. The authors would also like to thank Universiti Teknologi Petronas for providing full facilities and assistance during the research work.

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