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Effect of fuel particle size and blending ratio on syngas production and performance of co-gasification

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ABSTRACT

Shortage of feedstock supply often happens in biomass gasification. Thus, the co-gasification of blended biomass is a potential option to maintain feedstock supply for continuous gasification operations. The aim of this study is to investigate the effects of biomass blending ratio and biomass particle size on the syngas quality and performance of the co-gasification process. The co-gasification of wood chips/coconut shells was carried out in a downdraft gasifier at a 400 L/min airflow rate. The biomass blending ratio varies at 80/20, 50/50 and 20/80 (w/w) with biomass particle sizes of 5-10, 10-25 and 25-50 mm. The results show that small particle size favours gas composition. The highest H_2 (10.91%), CO (25.60%), and CH_4 (2.79%) levels were obtained from the 5-10 mm particle size at 80/20, 50/50, and 20/80 blending ratios, respectively. Higher HHV and gas yield were obtained at the 20/80 blending ratio with the 5-10 and 10-25 mm particle sizes, respectively. Cold gas efficiency varies from 54.37 to 65.52%. The trend shows that at smaller particle sizes, cold gas efficiency is higher, while in most cases, carbon conversion efficiency was found to be more than 90% during co-gasification. The syngas quality and performance of co-gasification were more sensitive to biomass particle size as compared to the blending ratio.

Keywords: co-gasification; particle size; blending ratio; biomass; syngas quality.

INTRODUCTION

Extensively increasing energy demand on finite fossil fuels and the high rates of pollutant emissions have created a prominent need for the adoption of sustainable, eco-friendly, and renewable energy sources [1-4]. One form of such energy source is biomass fuel. The conversion of biomass to syngas through the gasification process could be used as an alternative energy source to fill the future's energy demand gap [5, 6]. In addition, it would contribute to handling biomass waste effectively. It is projected that in the future, exploitation of different sources such as agricultural waste and forestry waste will be a significant contributor to the substitution of fossil fuel [6-8]. In many cases, the gasification process often encounters the problem of unsteady source of biomass feed throughout the year [9-12]. The gasification process may run using a single biomass source or multiple blends of feedstock. Numerous researchers have investigated the pyrolysis and gasification behaviour of various types of single biomass materials [13-17]. However, the co-gasification of different biomass materials is not fully understood, such as in terms of the interaction between one material with another. Interaction could exist among the volatile matters or between the fixed carbon of one biomass with other biomasses, or both. Each material has its own volatile releasing range, at specific temperatures of between 300-400 ºC [18]. Most probably, interactions happen between materials of similar nature such as the co-gasification of two or more biomass materials due to overlaps in their volatile releasing temperatures [6]. As for the steady-state supply of feedstock concern, it could be maintained through two approaches. The first one is by using a single feedstock for a certain period and changing the feedstock with another type when the first feedstock has ran out of its supply, while the second option is by mixing two or more materials into a blend to use as feedstock for the co-gasification. With the first option, the resulting syngas composition and performance of gasification would not be as consistent when the biomass type is changed. However, using the second option, the resulting syngas and performance of the co-gasification process remains constant when using the same blending ratio [6].

Although the co-gasification of coal and biomass has been intensively studied, the co-gasification of different biomass mixtures have yet to be extensively studied [19, 20]. Only a few researchers have reported on the co-gasification of different biomass materials. Kaewpanha et al. (2014) [21] studied co-gasified seaweed/Japanese cedar and reported the catalytic effects of alkali and alkaline earth metals on co-gasification. Alkali and alkaline earth metals improve gas yield, particularly in terms of the H_2 content. Buragohain et al. (2011) [22] studied the simulation results of co-gasification to assess the feasibility of co-gasification of different biomasses. It was reported that sawdust blend has high CO concentration and LHV together with low gas yield compared to other biomass blends. High temperatures and a high proportion of sawdust in blends can increase LHV values, whereas high air ratio can reduce LHV. Aigner et al. (2009) [2] studied the effect of temperature on tar elements and quantity of tar produced during the steam co-gasification of wood pellets and wood/straw pellets. It was reported that the type of biomass blend has no significant effect on tar production compared to the temperature of gasification. Inayat et al. (2015) [20] co-gasified blends of oil palm fronds/cane bagasse and wood/cane bagasse to explore the effect of blending ratio on temperature profile and syngas flare. He et al. (2012) [23] performed co-gasification of wood/straw, wood/miscanthus, and miscanthus/straw in order to identify the potential substitution of wood. H_2, CO, CH_4, and LHV increase as the miscanthus proportion increases in the blend, while the gas yield has no significant effect. In addition, a small quantity of $Ca(OH)_2$ in the blend improves syngas composition, LHV, gas yield, cold gas efficiency and carbon conversion efficiency. In another study, Pinto et al. (2015) [24] co-gasified rice husk and rice straw to minimize the associated problem of ash agglomeration and seasonal availability of feedstock. Singh et al. (2016) [25] conducted an experiment and a simulation study of the co-gasification of coconut shell and rubber seed shell in a 50 kW downdraft gasifier. Singh et al. investigated the effect ER on performance of co-gasification in terms of gas composition, heating value, gas yield, and conversion efficiency. They achieved good results with the simulation and experimental work. Kök et al. (1997) [26] reported that decreases in particle size cause more residual at the end of a combustion process. Yu et al. (2005) [27] found that decreases in particle size cause a decrease in the fraction of fixed carbon of bituminous coal. Zhang et al. (2007) [28] reported that an increase in particle size decreases volatile matter’s release and weight loss. Pyrolysis and gasification are relatively insensitive to particle size [29].

It is noted that the experimental results on the effect of particle size mainly focus on the biomass gasification in a fluidized bed gasifier, while the effect of particle size on gasification performance in a downdraft gasifier is often neglected due to lack of comprehensive studies [30]. Since very limited studies were carried out on the co-gasification of different biomass wastes, further studies are required to explore the performance potential of the co-gasification process and quality of syngas produced at different blending ratios and particle sizes. This paper investigates the effect of blending ratio and particle size on syngas composition and performance of co-gasification of blended feedstock of wood chips (WC) and coconut shells (CS) in a single throat downdraft gasifier.

MATERIALS AND METHODOLOGY

Collection, Preparation and Characterization of Raw Materials

Wood chips (acacia mangium) and coconut shells (*Cocos nucifera L*) were used as the feedstock for the current study. The stock of coconut shells was collected from local grocery stores that make coconut milk from fresh copra, and wood was collected from the landscape area within the campus of Universiti Teknologi PETRONAS. Fibre was removed from the outer surface of CS and the leftover flesh of copra inside the shells. Then the shells were crushed into different particle sizes according to the following categories; 5-10 (small), 10-25 (medium), and 25-50 mm (big) as presented in Figure 1.

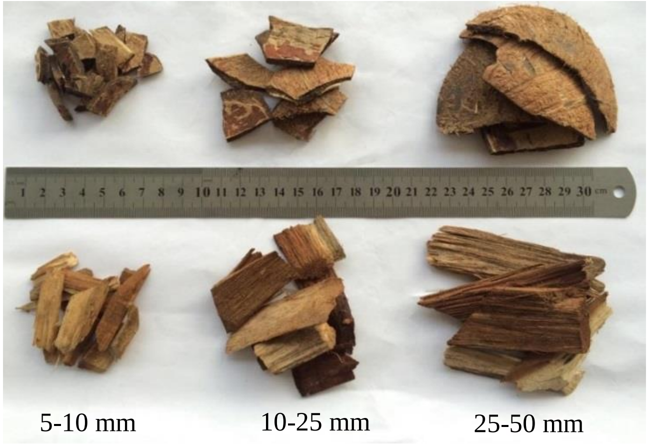

Figure 1. Different particle sizes of wood chips and coconut shells feedstock according to classification; small (5-10 mm), medium (10-25 mm), and large (25-50 mm).

Woody feedstock was chopped in the wood shredder. Both materials were sieved according to the required particle sizes as mentioned above. The feedstock was dried in an oven according to ASTM E871-82 [31]. Proximate analysis was performed according to ASTM E1755-01 [32] in a STA 6000 TGA analyser. The TGA results are helpful to study the kinetics of the biomass. The ultimate analysis was determined using a CHNS-932 analyser according to ASTM D3176-09 standard procedure [33]. The ultimate analysis includes C, H, O, N, and S contents of feedstock which helps to develop the biomass' empirical formula. The empirical formula was used to find the stoichiometric air for gasification. An AC-350 bomb calorimeter was used to measure the gross calorific value which is also referred to as higher heating value (HHV) according to ASTM D4809-00 [34]. The HHV of a feedstock helps to calculate its gasification efficiency. The basic chemical characteristics of WC and CS are shown in Table 1. CS has higher carbon, hydrogen, fixed carbon and heating values compared to the WC. Whereas, WC has a higher value of volatile matter. Beside this, both WC and CS have lower levels of nitrogen, sulphur, and ash content, implying that these biomass materials are most appropriate for co-gasification with negligible effects on the environment.

Table 1. Characterisation results of wood chips (WC) and coconut shells (CS).

Characterisation	Parameter	Biomass	
		WC	CS
Ultimate analysis (wt.%)	C	43.54	46.93
	H	3.59	3.96
	O*	51.70	48.21
	N	1.00	0.71
	S	0.16	0.19
Proximate analysis (wt.%)	MC	4.25	2.29
	VM	88.07	81.67
	FC	10.61	17.50
	Ash	1.32	0.83
Higher heating value (MJ/kg)		17.53	19.43

* On difference basis

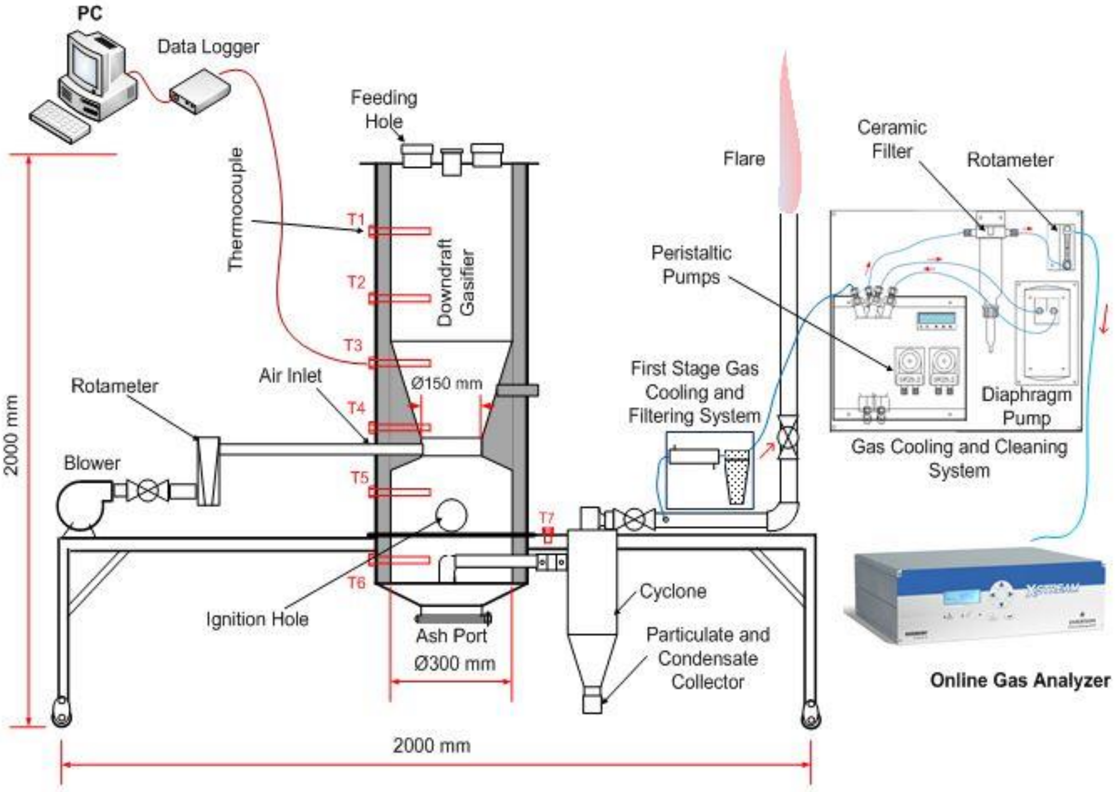

Figure 2. Experimental set-up of downdraft gasifier.

Experimental Set-up and Procedure

The experimental set-up used for the current study was a batch feeding downdraft gasifier as shown in Figure 2. Seven K type thermocouples with accuracies of ± 0.025 ℃ (T_1-T_7), were mounted on the vertical direction of the gasifier for temperature measurements which were recorded every 30 seconds by a TC-08 thermocouple data logger and computer. A pre-mixed blend of biomass feedstock was fed into the gasifier through feeding holes. Ignition was started through the ignition hole by using scrap paper. All lids were closed and the air was supplied by a blower at 400 L/min. The air flow rate was regulated and measured using a valve and a rotameter model VCF-131 with an accuracy of ±2%. After a steady gasification was achieved, the syngas was pumped to the online analyser through a rotameter at a controlled flow rate of one litre per minute. An X-Stream X2GP online gas analyser with accuracy of ±0.01% analysed the volumetric gas composition, for instance, CO, CO_2, and CH_4, and the H_2 on its LCD screen balance was assumed to be N_2. Extra syngas was ignited at the flare point. Char and ash were collected from the ash box and grated at the end of the experiment. Finally, the ash and char were weighed and the results were analysed and interpreted. Reproducibility of co-gasification experimental results was checked by conducting a set of three experiments at similar operational conditions. Three repetitions were enough to check the consistency of data.

RESULTS AND DISCUSSION

Effect of Blend Ratio and Particle Size on Syngas Composition

The effect of particle size and biomass blending ratio was investigated on syngas composition. The produced syngas mainly consists of CO, H_2, CH_4 and CO_2. The results depicted in Figure 3 are the average value of syngas composition from a stable regime of co-gasification experiments of different blending ratios and particle sizes of WC/CS. Results show that smaller particle size of blended biomass leads to higher H_2, CO and CH_4 concentrations in syngas. High peak gas composition is clearly shown in the 5-10 mm particles and the concentration gets lower when moving towards the big particle size (25-50 mm). Some other authors reported similar observations [35-39]. The reason of high yield results during the co-gasification of small particle size is the better heat transfer within smaller particle sizes and the large surface area of particles [40]. This is in accordance with the literature because the larger the particle size, the less effective the surface area for gasification at any instant, consequently producing syngas with low H_2 and CO content [41]. Decreases in H_2 with increases in particle size of biomass are also related to diffusion restrictions of volatile products generated during devolatilisation [35]. Among the syngas composition, only CO_2 yields show an increasing trend as particle size increases.

Higher hydrogen yields were obtained at 80/20 WC/CS blending ratio for all particle sizes except for the 10-25 mm particle size, where the 50/50 blending ratio has a slightly higher H_2 concentration value then the 80/20 blend ratio. The concentration of CO in syngas was also found to be higher at the 80/20 blending ratio in all co-gasification experiments except for the 5-10 mm particle size at a blending ratio of 50/50. These high yields of H_2 and CO during co-gasification were due to the domination of the water gas reaction, $C + H_2O \leftrightarrow CO + H_2$ which shows clear evidence of high H_2 and CO levels as shown in Figure 3. High concentration of CO and low content of CO_2 at 80/20 WC/CS blend implies the dominance of a boudouard reaction ($C + CO_2 \rightarrow 2CO$) which means that more CO and less CO_2 are produced in the syngas. High CO_2 production was obtained during the co-gasification of WC/CS blend at the 20/80 ratio.

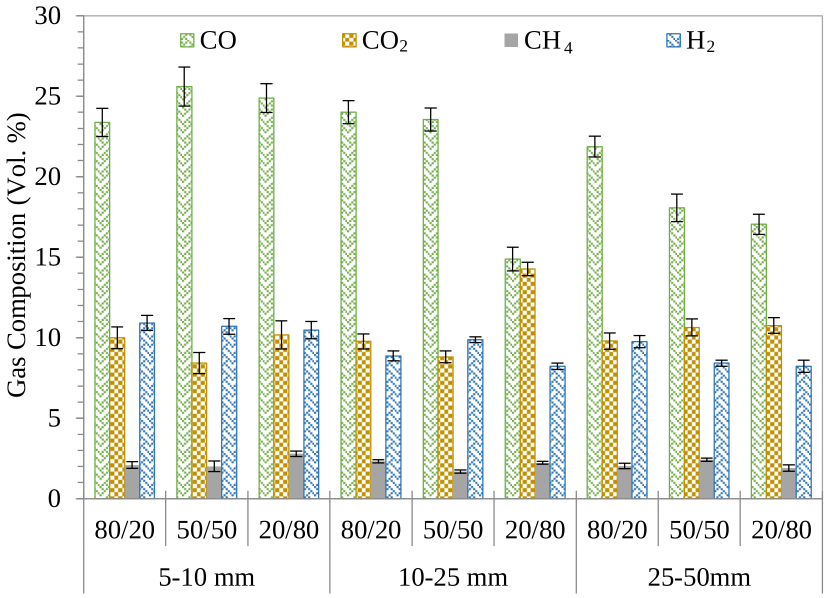

Figure 3. Effect of particle size and blending ratio on gas composition during the co-gasification of WC/CS.

Effect of Blend Ratio and Particle Size on Higher Heating Value

The heating value of syngas was calculated from the average syngas composition and the respective heating values of individual gases at normal temperature and pressure using [14]:

$$\mathrm{HHV}_{\mathrm{Syngas}} = \mathrm{HHV}_{\mathrm{CO}} \times X_{CO\%} + \mathrm{HHV}_{\mathrm{H_2}} \times X_{H_2\%} + \mathrm{HHV}_{\mathrm{CH_4}} \times X_{CH_4\%} \tag{1}$$

where HHV of CO, H_2 and CH_4 are 12.63 MJ/Nm^3, 12.74 MJ/Nm^3 and 39.82 MJ/Nm^3, respectively [42], and $X_{CO\%}$, $X_{H_2\%}$ and $X_{CH_4\%}$ denote the volumetric percentage of CO, H_2 and CH_4 in the dry syngas respectively [14]. The effect of particle size and blending ratio on the syngas' HHV during the co-gasification of WC/CS blends are shown in Figure 4. The HHV of syngas has a decreasing trend as the particle size of biomass increases. The highest value of HHV was obtained from the smaller particle size of 5-10 mm, followed by 10-25 mm and 25-50 mm. There are numerous reasons for a high value of HHV at smaller sizes. For instance; a smaller size of biomass can easily mix into the uniform blend, producing more consistent gas composition. Moreover, small biomass particles rapidly release volatile matter compared to big particles [29]. It can be explained by the large surface area of smaller particles which is associated with better heat transfer as compared to big particles, and consequently it improves the gas composition and higher HHV of syngas at smaller particle sizes [29]. For the 10-25 mm and 25-50 mm particle sizes, the HHV results for the 80/20 W/CS blend were higher compared to other blending ratios, whereas the 5-10 mm particle size showed lower results for the 80/20 blending ratio, which is 8% lower than the 20/80 WC/CS blend. The HHV of syngas shows a decreasing trend as the CS proportion increased in blend at particle sizes of 10-25 mm and 25-50 mm, while the co-gasification of the 5-10 mm particle size blended biomass shows a reverse trend.

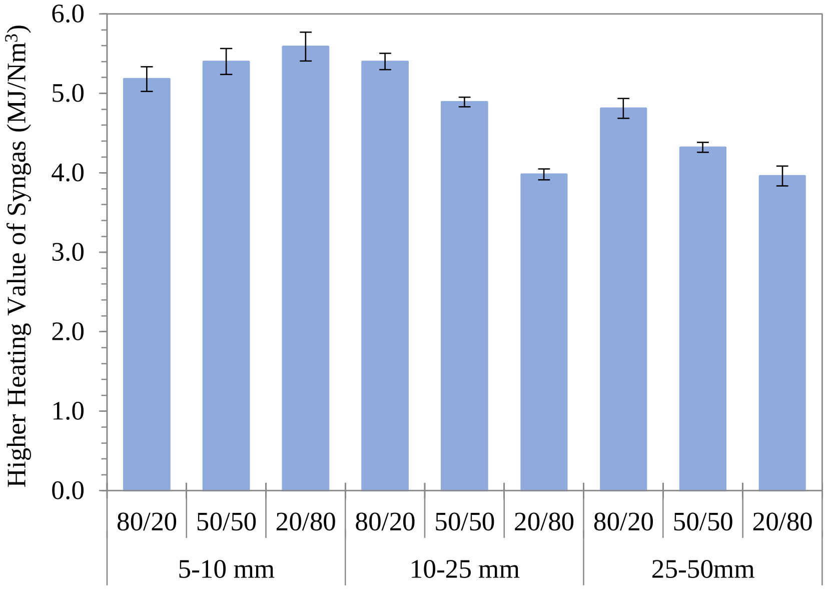

Figure 4. Effect of particle size and blending ratio on higher heating value of syngas during the co-gasification of WC/CS.

Effect of Blend Ratio and Particle Size on Gas Yield

Figure 5 illustrates gas yield as a function of particle size with different blending ratios of blended feedstock. Gas yield was determined using an indirect method of a nitrogen balance approach relation calculated using [43]:

$$Y = \frac{Q_a \times 79\%}{W_b(1 - X_{\mathrm{ash}})\mathrm{N}_2\%}\ \mathrm{Nm}^3/\mathrm{kg} \tag{2}$$

where Y is the gas yield (Nm^3/kg), Q_a is the flow rate of air (Nm^3/h), W_b is the flow rate of biomass (kg/h), X_{ash} is the ash content in biomass (% weight), and N_2% is the volumetric percentage of nitrogen in the dry syngas. It was assumed that air has a standard composition of 21% oxygen and 79% nitrogen, and all of the oxygen content in the air had reacted with the feedstock during the gasification process. In addition, the syngas consisted of CO, H_2, CO_2, CH_4, and N_2, of which N_2 was determined using the difference method. The results show that an increase in particle size of feedstock leads to a significant increase in the gas yield. The maximum value of gas yield was obtained from a 10-25 mm particle size followed by 25-50 mm and 5-10 mm. It is anticipated that large particles have significant devolatilisation time during the gasification process as compared to small particles. Large particles of feedstock were sustained for longer gasification periods and released more gaseous products compared to small particles. The effect of the blending ratio on gas yield is shown in Figure 5, where particle size of 10-25 mm has a constant increasing trend as CS proportion increases in blend, which implies that more CS content in the blend favours the enchantment in the gas yield. A similar trend can be observed for big particles of 25-50 mm feedstock. Therefore, for both particle sizes of 10-25 mm and 25-50 mm, the 20/80 WC/CS blend has peak value. However, smaller particle sizes of 5-10 mm showed a reverse trend. The 5-10 mm blended feedstock has a lower value of gas yield compared to other particle sizes and its 50/50 blend has higher gas yield. It was probably due to the very packed particle conditions of the feedstock inside the gasifier which has an adverse effect on air passage, consequently weakening the interaction between feedstock and air. As a result, a lower gas yield was recorded during the co-gasification of the 5-10 mm particles.

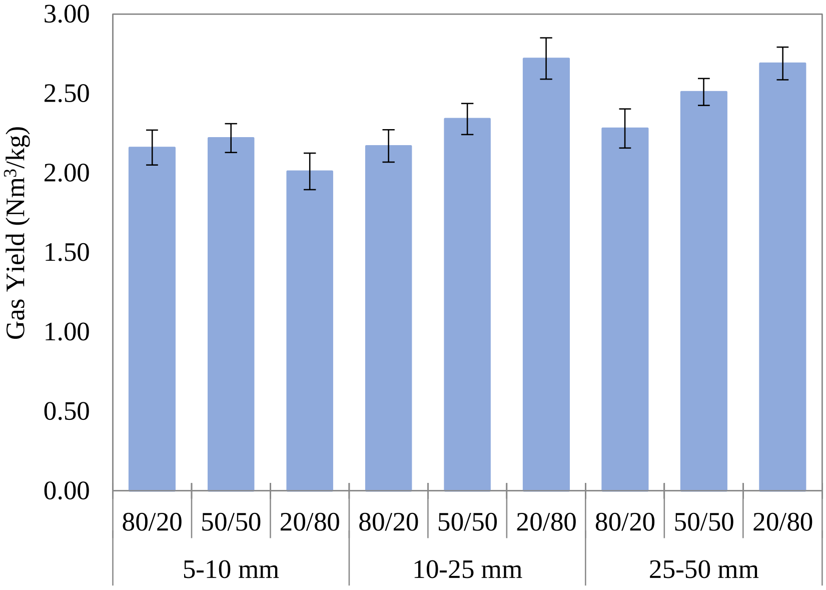

Figure 5. Effect of particle size and blending ratio on gas yield during the co-gasification of WC/CS.

Effect of Blend Ratio and Particle Size on Cold Gas Efficiency

Figure 6 depicts the effect of particle size and blending ratio on cold gas efficiency (CGE) during the co-gasification of WC/CS blends. Cold gas efficiency (η_{th}) explains how much solid fuel energy is converted into gaseous fuel energy. In other words, it also represents operational efficiency in terms of thermal energy or system efficiency [44]. The gas yield was determined using [14, 41]:

$$\eta_{th} = \frac{H_g\,(\mathrm{MJ/Nm^3}) \times Y\,(\mathrm{Nm^3/kg})}{H_b\,(\mathrm{MJ/kg})} \times 100 \tag{3}$$

where H_g (MJ/Nm^3) is the higher heating value of syngas, Y is the gas yield (Nm^3/kg) and H_b (MJ/kg) is the HHV of feedstock determined during the characterization of feedstock. The trend of CGE shows that as the particle size of the feedstock increases, the cold gas efficiency of the process decreases. It could be due to the higher gas yield as CGE is the ratio of the syngas heating value to the heating value of feedstock according to Eq.(3) [14, 45]. However, a higher value of CGE was obtained from the 10-25 mm particles at the 80/20 blend ratio followed by the 5-10 mm and 25-50 mm particle sizes. For the 5-10 mm particle size, the blending ratio of 80/20 was slightly out of the existing trend when compared to the other particle sizes; therefore, the 50/50 WC/CS blend obtained higher CGE values specifically for this particle range. The lower CGE value of 80/20 was due to the low value of HHV at the 80/20 blend compared to the other blends using the same particle size. The cold gas efficiency has a decreasing trend among the blending ratio. As the WC proportion decreases for the blend, the value of CGE also decreases. A similar trend can be seen for both 10-25 mm and 25-50 mm particle sizes [45]. It is suggested that higher WC proportions in blend is favourable for the gasification process efficiency.

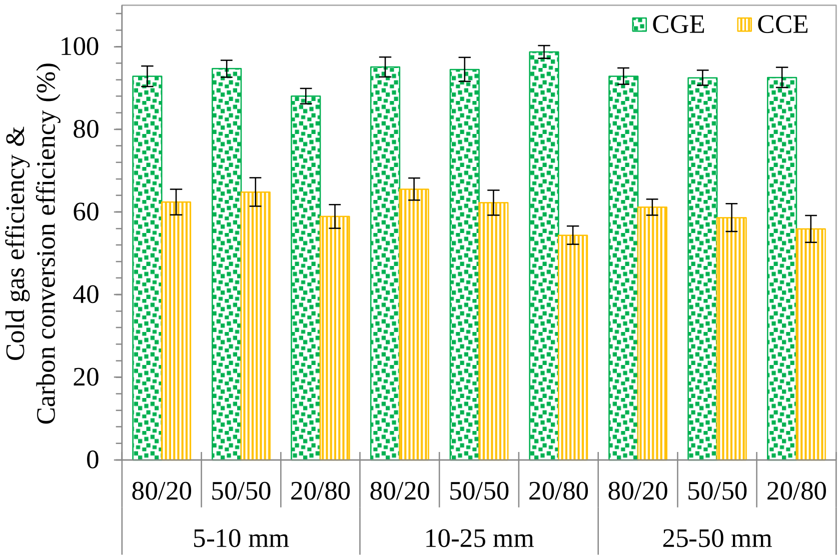

Figure 6. Effect of particle size and blending ratio on cold gas efficiency (CGE) and carbon conversion efficiency (CCE) during the co-gasification of WC/CS.

Effect of Blend Ratio and Particle Size on Carbon Conversion Efficiency

Figure 6 illustrates the carbon conversion efficiency (CCE) as a function of particle size and blending of different biomass materials. The carbon conversion efficiency (η_c) was calculated based on the average volumetric percentage of CO, CO_2 and CH_4 content in the syngas, [41]:

$$\eta_c = \frac{Y(\text{CO\% vol.} + \text{CO}_2\text{\% vol.} + \text{CH}_4\text{\% vol.}) \times M_C}{22.4 \times \text{C\%}} \times 100 \qquad (4)$$

where C% is the mass percentage of carbon in the feedstock obtained from the ultimate analysis. Y is the gas yield in Nm^3/kg, where the % vol. denotes the volumetric percentage of CO, CO_2, and CH_4 in the syngas, whereas M_C is the atomic mass of carbon atom in grams and 22.4 is the volume of one mole of an ideal gas in litres at standard temperature and pressure. The CCE results of co-gasification obtained were quite high at more than 90% for all particle sizes and blends except for the 20/80 blend using the 5-10 mm particle size. The high level of CCE of the WC/CS co-gasification was due to the high reactivity of WC and CS blends because both feedstock are plant-based in nature, and plant-based biomasses are normally more reactive under gasification [41]. In addition, WC and CS have high volatile matter and low fixed carbon and ash as shown in Table 1. The results show that the 10-25 mm particles are more supportive of the carbon conversion. Karimipour et al. (2013) [29] reported a similar trend of CCE in a fluidized bed gasifier. The Co-gasification results of 10-25 mm particle size showed high CCE values for different blends of biomass materials. The increase in CCE that happens with the increase in particle size suggests that the increase in residence time counterbalances the decrease in effective surface area. At large particle sizes of 25-50 mm, the CCE level is almost similar for each blending ratio, so CCE levels do not show any noticeable sensitivity for large particle sizes and any blending ratiod [29]. Whereas, for small particle sizes of 5-10 mm, the 50/50 blend had higher CCE values, followed by the 80/20 and 20/80 WC/CS blends.

CONCLUSIONS

The co-gasification of WC/CS blended feedstock was successfully carried out in a downdraft gasifier with 80/20, 50/50, and 20/80 WC/CS blending ratios and particle sizes of 5-10, 10-25, and 25-50 mm. The effects of blending ratio and particle size were investigated on syngas quality (gas composition and HHV of syngas) and performance (gas yield, CGE and CCE) of co-gasification. Quality of syngas was improved for small particles compared to large particles at the 80/20 blending ratio. The HHV of syngas, H_2, CO, and CH_4 contents increased from 3.96 MJ/Nm^3 to 5.59 MJ/Nm^3, 9.76% to 10.91%, 17.05% to 25.60%, and 1.90% to 2.79% respectively as particle size decreases from 25-50 mm to 5-10 mm. Gas yield was improved from 2.01 Nm^3/kg to 2.69 Nm^3/kg as the particle size increased from 5-10 mm to 25-50 mm. CGE increased from 58.63% to 64.81% as particle size decreased from 25-50 mm to 5-10 mm, and the CCE levels were quite high. The quality of syngas and performance of co-gasification were more sensitive to small particle size. However, gas yield was on a reverse trend, and in most cases the 80/20 blend was found to be the optimum blend. This study was limited to air as the gasifying medium, so it is suggested that steam co-gasification of different biomasses should be explored on to improve syngas composition.

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