PHILIPP AGRIC SCIENTIST
Vol. 106 No. 1, 66-74
March 2023

ISSN 0031-7454

Air and Air-Steam Gasification of Coconut Shell in a Fluidized Bed

Keynty Boy V. Magtoto[1,*], Rossana Marie C. Amongo[1], Sergio C. Capareda[2], and Ronaldo B. Saludes[1]

[1]Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, Laguna, 4031, Philippines
[2]Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843, United States

[*]Author for correspondence; Email: akvmagtoto@up.edu.ph

Received: May 11, 2022/ Revised: January 24, 2023/ Accepted: January 30, 2023

Its abundance in tropical countries, high volatile combustible matter (83.51%), and energy content (18.68 MJ kg^{-1}) make coconut shells a good biomass resource and a promising feedstock for gasification. In gasification, different mediums such as air, steam, oxygen, or their combinations can be used to react with the solid carbon and heavy hydrocarbons of biomass. Hence, the effects of using an air-steam mixture as a gasifying agent for the bench-scale fluidized bed gasification of coconut shells were studied. The steam-to-carbon ratio (SCR) was varied to evaluate its effect on the resulting syngas quality and gasification performance while the equivalence ratio was maintained at 0.25 and the bed temperature was kept at 700°C. Results revealed that the optimum SCR is 0.6, where peak values of hydrogen (H_2) and methane (CH_4) content, hydrogen-to-carbon monoxide ratio (H_2/CO), higher heating value (HHV), cold gas efficiency (CGE) and carbon conversion efficiency (CCE) were observed. Furthermore, the use of the air-steam mixture (SCR 0.6) as a gasifying agent was compared with the conventional air gasification. Results showed a significant increase in syngas quality in terms of H_2 content (4.70–5.82%), H_2/CO (0.30–0.39), and CH_4 content (3.53–4.38%). The syngas heating value and gasification performance revealed statistically similar improvement: HHV from 4.95 to 5.41 MJ Nm^{-3}, CCE from 77.64 to 81.75%, and CGE from 47.99 to 51.01%. Moreover, air-steam gasification produced less CO_2 (13.42 CO_{2mol} $kg_{biomass}^{-1}$) and had higher energy recovery (49.67%).

Keywords: coconut shell, fluidized bed gasification, gasifying agents, steam-to-carbon ratio

Abbreviations: mol_s—number of moles of steam (mol), mol_b—number of moles of biomass (mol), FR_s—flow rate of steam (g min^{-1}), FR_b—feed rate of biomass (g min^{-1}), C—carbon content of biomass (%), MW_C—molar weight of carbon (12.011 g mol^{-1}), MW_s—molar weight of steam (18 g mol^{-1}), η_{cold}—cold gas efficiency (%), M_{sg}—mass flow rate of syngas (kg min^{-1}), M_b—mass flow rate of biomass (kg min^{-1}), HHV_{sg}—high heating value of syngas (MJ kg^{-1}), HHV_b—high heating value of biomass (MJ kg^{-1}), η_{carbon}—carbon conversion efficiency (%), f_{sg}—syngas volumetric flow rate (Nm^3 kg^{-1}), Y_i—%mole (v/v) of each gas component of syngas (%)

INTRODUCTION

The Philippines is a tropical country with a total land area of approximately 30 million ha, 41% of which is utilized for agricultural purposes. The country also holds the largest number of coconut trees in the world with approximately 500 million trees. Consequently, coconut is among the top three most produced agricultural crops in the country along with sugarcane and paddy rice, with an average annual production of 15 million t/yr (Go et al. 2019). With this much production, coconut biomass contributes almost 10.4 million tons of waste from husks, shells, and fronds (Zafar 2021). Since these wastes can be sourced almost anywhere in the country and do not compete with food consumption, they can be considered as a potential biomass resource (Canabarro et al. 2013).

With the increasing effects of climate change and fossil fuel depletion, biofuels—fuels derived from biomass—have been receiving much interest from around the world due to their carbon neutrality, which enables the carbon dioxide released during the burning of biomass to be absorbed back by plants through photosynthesis (Suh et al. 2014). Aside from lessening dependence on fossil fuels, the use of biomass waste for energy generation also addresses waste disposal issues.

There are two general pathways by which biomass is converted to biofuels—biochemical and thermochemical treatment technologies. Biochemical processes use microorganisms or other living organisms to break down the biomass into biofuels. Compared to other processes, biochemical methods such as biophotolysis of water using algae and cyanobacteria, photocomposition of organic compounds by photosynthetic bacteria, fermentative hydrogen production from organic compounds, and hybrids system of photosynthetic and fermentative bacteria produce large amounts of hydrogen (60 – 90 % v/v). However, the low efficiency and high production costs of biochemical processes make them less attractive for industries (Das and Veziroğlu 2001). On the other hand, thermochemical conversion breaks down biomass through the application of heat and pressure. The four types of thermochemical processes are combustion, pyrolysis, gasification, and liquefaction (Kalinci et al. 2009).

Existing research has focused on pyrolysis and gasification because of better fuel yields. Biomass subjected to pyrolysis is heated in the absence of an oxygen agent which results in bio-oil, whereas biomass treated in gasification is subjected to an oxygen-starved environment which results in gaseous fuels (McKendry 2002). In general, gasification results in higher efficiencies compared to other thermochemical processes (Sharma and Sheth 2016). Previous studies have also explored the use of various feedstocks such as wheat straw (Ergudenler and Ghaly 1993), pine sawdust (Lv et al. 2004), rice hull (Boateng et al. 1992), and coconut shell (Ganapathy Sundaram and Natarajan 2009; Moghadam et al. 2014; Yahaya et al. 2019) under different operating conditions.

Gasification produces low-molecular-weight gases such as carbon monoxide and hydrogen gas gaseous fuel, which is also known as producer gas, synthesis gas, or simply "syngas". Aside from syngas, gasification also produces solid (biochar) and liquid (tar) by-products. The syngas can be directly used for heat and power generation. The type of gasifying agent such as air, steam, oxygen, or their combinations affects the reaction; hence, the quality of the syngas also varies depending on the conversion path. Gasification involves five major gas reactions which are dominantly endothermic (Table 1). Partial combustion of biomass is promoted by introducing small amounts of oxygen in order to react with carbon and drive the endothermic reactions (Basi 2013).

Table 1. Major gasification reactions.

Gasification Reactions	Reaction	Enthalpy (kJ/mol)	Type of Reaction
Water-gas	$C + H_2O \longleftrightarrow CO + H_2$	131	endothermic
Water-gas shift	$CO + H_2O \longleftrightarrow CO_2 + H_2$	-41.2	exothermic
Boudouard	$C + CO_2 \longleftrightarrow 2CO$	172	endothermic
Hydrogasification	$C + 2H_2 \longleftrightarrow CH_4$	74.8	endothermic
Methanation	$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$	-206	exothermic

The use of air as the medium for gasification reactions produces syngas with low heating value (4 – 7 MJ Nm^{-3}) primarily due to the dilution effect of nitrogen and the low hydrocarbon content. Hence, air gasification is suitable for heat and power generation but not for the production of valuable chemicals and liquid fuels (Gil et al. 1997). When steam is used as the gasifying medium, the heating value of syngas ranges from 10 – 16 MJ Nm^{-3} with high hydrogen composition (Ptasinski et al. 2009). The reactions in steam gasification are driven by water and gas as well as their shift reactions. However, external heating of steam is required to maintain the high operating temperature and to avoid the degradation of endothermic reactions. Lastly, oxygen is considered the best medium in terms of the heating value of the resulting syngas (12 – 28 MJ Nm^{-3}). However, the high capital cost of oxygen production makes it not feasible for industrial-scale utilization (Schuster et al. 2001).

The study aimed to evaluate the effect of using air and air-steam mixture as gasifying agents for fluidized bed gasification of coconut shells. The specific objectives were to analyze the effects of varying steam-to-carbon ratios on the composition of syngas, H_2/CO, HHV, CGE, and CCE as well as to compare air gasification with air-steam gasification in terms of energy recoveries and carbon dioxide emissions.

MATERIALS AND METHODS

Coconut Shell Pre-processing and Characterization

The coconut shells used in the study came from a plantation in Nagcarlan, Laguna, Philippines. The freshly acquired coconut shells were immediately subjected to sun-drying for 2 d to avoid fungal formation. The dried coconut meat residues in the shells were removed and the resulting meat-free shells were subjected to size reduction using a hammer mill with a sieve size of 2 mm. To be cleared for transport to Texas A&M, USA where the experiment was conducted, the coconut shells were exposed to methyl bromide for 24 h as a phytosanitary treatment required by the Bureau of Plant Industry (BPI). The effect of the said treatment was not evaluated in the results.

Proximate analysis was done following ASTM E871 (Standard Method for Moisture Analysis of Particulate Wood Fuels) for moisture content determination, ASTM 872-82 (Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels) for volatile combustible matter, and ASTM E1755 (Standard Test Method for Ash in Biomass) for ash, while the fixed carbon content was computed by difference. On the other hand, ultimate analysis was done following the ASTM Standards such as ASTM E 777-08 for carbon and hydrogen, ASTM E 775-87 for sulfur, and ASTM E 778-08 for nitrogen. Percent of oxygen was determined by difference.

The higher heating value of the coconut shell was determined according to ASTM D5865 (Standard Test Method for Gross Calorific Values of Coal and Coke) using Parr isoperibol bomb calorimeter (Model 6200, Parr Instrument Company, Moline, IL). Finally, ASTM E871 (Standard Method for Moisture Analysis of Particulate Wood Fuels) was used for moisture content determination.

Bench-scale Fluidized Bed Gasifier Setup

The schematic of the bench-scale fluidized bed gasifier used in the study is shown in Fig. 1. The reactor was a 15 x 84 cm tube made from AISI 316 stainless steel. An electric tube furnace was used to heat the reactor. The feedstock, confined in the hopper, was introduced at the bottom of the reactor through an auger shaft. The atmospheric air was sourced from an air compressor connected at the bottom of the reactor and at the upper part of the hopper. This connection was designed to prevent the backflow of biomass due to the pressure induced by the gasification reactions. The top of the reactor had three outlets: a port for the steam input, a k-type thermocouple, and a port to measure the pressure at the lower bed region. The thermocouple was placed at the bottom part of the bed material to monitor the bed temperature. A pressure tube was placed to monitor the fluidization of the bed material. The bed material used in the study was a refractory calcined mullite material (CE Minerals, Andersonville, GA) consisting of S_iO_2 (50%) and Al_2O_3 (46.8%).

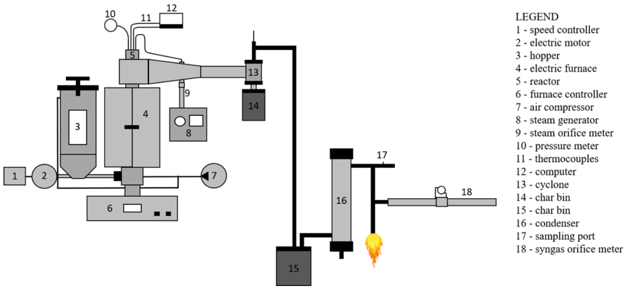

Fig. 1. Schematic diagram of the bench-scale fluidized bed gasifier at BAEN lab, TAMU.

The steam generator was set at 70 psi. The steam's mass flow rate was calibrated with the manometer readings connected to an orifice meter. The tube connecting the steam generator and the steam port was coiled with a heater cord that can heat up to 400°C. The entry point of steam in the reactor was positioned at its pyrolysis zone, 2.5 cm above the bed.

The resulting solid particles (char) were separated from the syngas through the cyclones. The setup has two char bins to increase the efficiency of separation. Syngas was further cleaned by passing through a condenser, removing moisture and liquid tars. Finally, the syngas outlet had three ports: a sampling port, a flaring port, and another connected to an orifice meter to measure the flow rate of syngas.

Experimental Design for Varying SCR

The steam-to-carbon ratio (SCR) was varied to evaluate its effect on the resulting syngas composition and heating value. The SCR was computed on a molar basis using Eq. 1. The SCR values considered in the study were 0 (no steam), 0.3, 0.6, 0.9, and 1.2.

The reaction temperature has significant effects on the syngas quality and gasification performance. Generally, higher temperatures are desired since gasification is dominated by endothermic reactions. At elevated temperatures, higher reaction rates are expected. According to Yahaya et al. (2019) and Moghadam et al. (2014), the optimum temperature for coconut shells gasification was determined at 900°C and 950°C, respectively. However, in this study, the bed temperature was set to only 700°C due to equipment limitations. The equivalence ratio (ER) was held at 0.25 as the determined optimum according to the study of Wan Ab Kharim Ghani et al. (2009) on air-gasification of coconut shells. To achieve the desired ER, the feed rate was maintained at 56.5 g min^{-1}, while the airflow rate was set to 45 l pm.

$$SCR = mol_s/mol_b = FR_s/[(FR_b \times C)/MW_c] \times MW_s \qquad (1)$$

The experiment started with the SCR set to zero (0). After attaining a stable condition for 10 min, gas sampling was done using a syringe and tedlar bags. The steam flow rate was then increased to achieve the next SCR setting, which continued until a gas sample was collected at the SCR 1.2. This was done in three replicates. The samples were analyzed using gas chromatography with a thermal conductivity detector that measured the relative concentrations of hydrogen (H_2), oxygen (O_2), nitrogen (N_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), propylene (C_3H_6), and propane (C_3H_8).

One-way ANOVA was used for the statistical analysis where the null hypothesis was tested at a 95% level of confidence. The parameters such as H_2, H_2/CO, CO/CO_2, HHV, CGE (Eq. 2), and CCE (Eq. 3) were analyzed.

$$\eta_{cold} = (M_{sg} \times HHV_{sg})/(M_b \times HHV_b) \qquad (2)$$

$$\eta_{carbon} = 12/22.4 \times f_{sg} \times [(Y_{CO} + Y_{CO2}) + Y_{CH4} + 2\times (Y_{C2H2} + Y_{C2H4} + Y_{C2H6}) + 3\times (Y_{C3H6} + Y_{C3H8})]/[C+M_b] \qquad (3)$$

Comparative Analysis of Air Gasification and Air-steam Gasification

Air gasification and air-steam gasification of coconut shells were compared in terms of syngas quality, gasification performance, CO_2 production, and energy recovery. The bed temperature and ER were still maintained at 700°C and 0.25, respectively.

Separate experimental runs were done for air gasification and air-steam gasification. The SCR of the air-steam gasification was set to its determined optimum value. After attaining the desired experimental conditions of each setup, gas sampling was done every 5 min for 15 min. Syngas quality was determined through gas chromatography and the gasification performances were calculated.

On the other hand, the CO_2 emissions were characterized from the produced syngas and chars. The collected chars from the air and air-steam gasification experiments were then subjected to combustion and was done in three replicates using Parr isoperibol bomb calorimeter. For each trial, a gas sample was collected after the bomb canister was pressurized with oxygen, which served as the basis for normalizing the gas analysis. After the combustion, gas samples were collected and analyzed using gas chromatography, where relative concentrations ($\%_{v/v}$) of oxygen, nitrogen, and carbon dioxide were determined. The syngas produced from gasification was assumed as an end product, and the CO_2 moles of syngas were simply added to the CO_2 moles released from the combustion of chars.

RESULTS AND DISCUSSION

Coconut Shell Characteristics

Table 2 presents the characteristics of the coconut shell. The proximate analysis revealed that the coconut shell used in the study had 83.51$\%_{wt}$ volatile combustible matter, 15.55$\%_{wt}$ fixed carbon, and 0.95$\%_{wt}$ ash content. The coconut shell containing high VCM content indicates its suitability for thermal conversion processes that focus on gaseous products. The low ash content also suggests that coconut shell has a very low tendency to exhibit fouling and slagging during the gasification process (Rajvanshi 1986).

Table 2. Characterization results of coconut shell.

Properties	Value
Proximate analysis $_{\text{dry basis}}$ ($\%_{wt}$) [a]	
VCM, %	83.51 ± 0.78
Ash, %	0.95 ± 0.06
FC, %	15.55 ± 0.73
Ultimate analysis $_{\text{dry basis}}$ ($\%_{wt}$)	
C	39.80
H	4.74
O [b]	54.42
N	0.08
S	0.01
Moisture Content $_{\text{as received}}$ ($\%_{wt}$) [a]	6.94 ± 0.03
HHV, MJ/kg [a]	18.68 ± 0.24

[a] analysed in replicates n = 3

[b] analysed by difference

The gross calorific value was measured in terms of higher heating value (HHV), which represents the heat of combustion released relative to liquid water as the product. The HHV of the coconut shell was determined to be 18.68 MJ kg^{-1}—classified as lignocellulosic biomass according to Stahl et al. (2006). In terms of moisture content, the biomass has only 6.94$\%_{wt}$ after 2 d of sun-drying. In general, most biomass with 15% moisture can be subjected to gasification.

Based on the ultimate analysis, the complete combustion equations of coconut shells for air and air-steam gasification were established, which served as the basis for the stoichiometric air-to-fuel ratio.

Effect of Varying SCR on Syngas Composition

The study determined the effect of using an air-steam mixture as the gasifying agent for fluidized bed gasification of coconut shells at varying SCRs (0, 0.3, 0.6, 0.9, and 1.2). Fig. 2 shows the average composition of the resulting syngas from the different SCR settings.

In general, it was observed that 70 – 75% of the syngas composition was made up of nitrogen and carbon dioxide, which are zero-energy gases. The high concentration of nitrogen in the syngas was due to the usage of air as a part of the gasifying agent. On the other hand, hydrocarbons like acetylene, ethylene, ethane, and propylene accounted for an average of only 1.5$\%_{v/v}$.

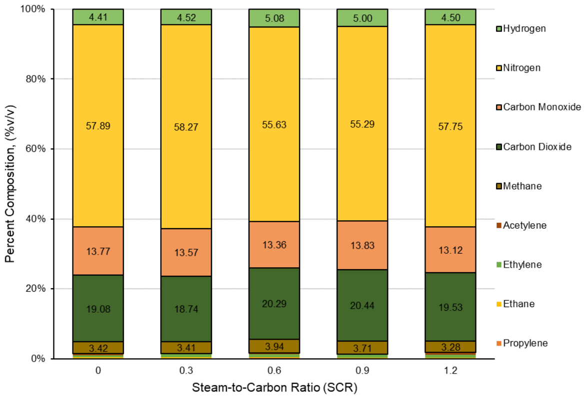

Fig. 2. Average syngas composition produced at different SCRs.

Although these hydrocarbons have low volumes, they accounted for 18.21% (0.79–1.06 MJ Nm^{-3}) of the total energy content because of their relatively higher HHV equivalents.

The trends of the H_2 content, hydrogen-to-carbon monoxide ratio (H_2/CO), and carbon monoxide-to-carbon dioxide ratio (CO/CO_2) are presented in Fig. 3.

The hydrogen content displayed an increasing trend where it peaked at SCR 0.6 with a value of $5.08\%_{v/v}$ (Fig. 3a). Further increase in SCR or steam input resulted in a decreasing pattern. This can be explained by the impact of the endothermic reactions on the operating temperature, which in turn limits the reforming reactions.

According to Le Chatelier's principle, the dynamic equilibrium of reactions always shifts to counteract the change made. If the number of reactants is increased, then this will drive the reaction to produce more products. In this study, by adding more steam, steam-reforming reactions such as the water-gas (WG), water-gas shift (WGS), and steam-methane reforming reactions were all promoted. Hence, an increasing trend in $\%H_2$ concentration was observed from SCR 0 to SCR 0.6.

Considering the reaction thermodynamics indicated in Table 1, although the WGS was slightly exothermic (-41.2 kJ mol^{-1}), the heat released was not enough to compensate for the heat absorbed by the WG (+131 kJ mol^{-1}) and steam -methane reforming reaction (+206 kJ mol^{-1}). Therefore, the reforming reactions in air-steam gasification were dominated by endothermic reactions.

For endothermic reactions (WG and steam-methane), the temperature is considered one of the reactant variables. From a chemical equilibrium standpoint, endothermic reactions are strengthened with increasing temperatures, which will result in higher reaction rates and produce more products. According to Li et al. (2019), several studies on biomass steam gasification found that hydrogen concentration was promoted by increasing the reaction temperature. Higher temperature supplies the energy required by endothermic reactions thereby enhancing the hydrogen content of the syngas (LV et al. 2003; Gupta and Cichonski 2007). However, since this study was limited to 700°C, steam reforming reaction rates were most probably limited as well. Although the FBG setup used was not equipped to monitor the changes in the reaction temperature, many studies found similar results indicating that excessive steam input decreases the operating temperature, which results in reduced syngas quality (Gil et al. 1997; Wang et al. 2007; Miccio et al. 2009; Alauddin et al. 2010; Chen et al. 2013). Hence, higher reaction temperatures and optimized steam inputs are recommended to yield higher hydrogen concentrations.

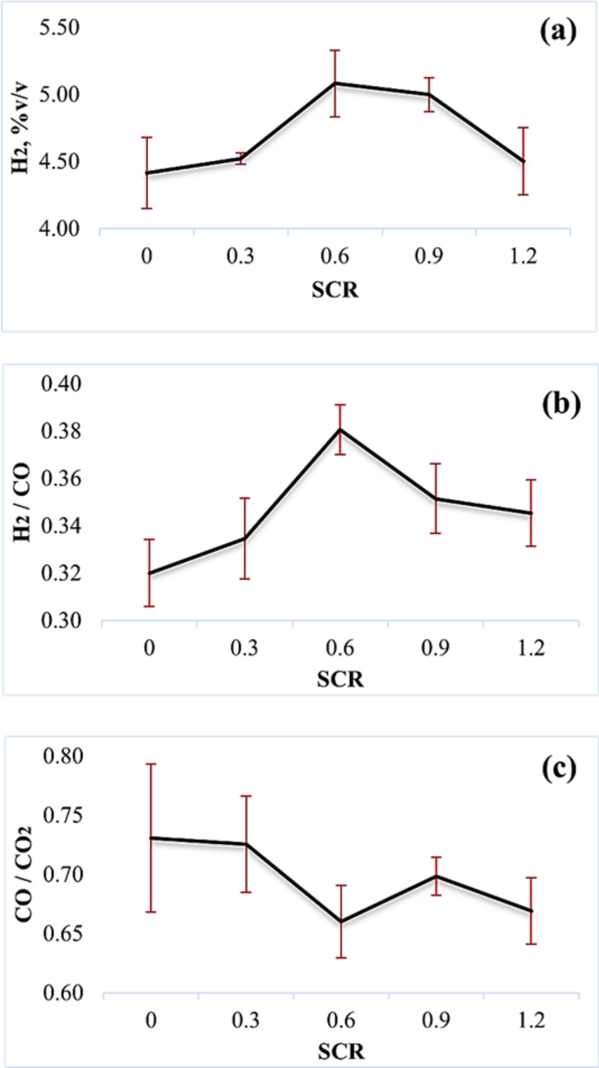

Fig. 3. The (a) H_2, (b) H_2/CO and (c) CO/CO_2 of syngas produced at varying SCR.

ANOVA revealed that in terms of hydrogen content, SCRs have statistically similar results (*p*-value = 0.1332). This result suggests that steam had undergone minimal reforming at a temperature of 700°C. Moghadam et al. (2014) determined that the hydrogen production from air-steam gasification of coconut shell has an increasing pattern with increasing temperature treatment. The % hydrogen of syngas was observed at the highest reaction temperature (1100°C).

The H_2/CO ratio represents the degree of WGS reactions that happened during the gasification process. In WGS, steam reacts with carbon monoxide to produce hydrogen and carbon dioxide. Therefore, mixing steam as a gasifying agent increases hydrogen content at the expense of carbon monoxide. As shown in Fig. 3b, H_2/CO increased when SCR was increased from 0 to 0.6 then decreased at higher SCRs. The determined peak value of 0.381 is lower than most biomass (0.7 − 1.5). Syngas with high H_2/CO nearing 2.0 has the potential for further synthesis of methanol, ethanol, and dimethyl ester. For syngas with a low H_2/CO ratio, the quality can be improved by incorporating a methane reformer and/or water-gas-shift reactor, but this will incur higher capital and operating costs (Zheng et al. 2018). Although the increase in H_2/CO ratio entails higher syngas quality considering its suitability for further synthesis, it will have a minimal effect on the energy content of syngas because H_2 and CO have almost the same heating values.

The CO/CO_2 ratio, on the other hand, represents how much of the carbon content of the biomass is converted to CO, the desired component of the syngas, instead of carbon dioxide. Fig. 3c revealed that there was a general decreasing trend of CO/CO_2 ratio with increasing SCR, which is similar to the studies of Lv et al. (2004) and Chun et al. (2011). Steam promotes WGS that converts CO to CO_2 and H_2. Therefore, an increasing trend in H_2/CO ratio would mean the opposite trend for the CO/CO_2 ratio. The lowest CO/CO_2 ratio (0.66) is determined at SCR 0.6. One-way ANOVA revealed that both the H_2/CO ratio and CO/CO_2 ratio had statistically similar results for all SCR settings with *p*-values of 0.1086 and 0.6232, respectively.

Effect of Varying SCR on CCE, CGE, and HHV

Carbon conversion efficiency (CCE) and cold gasification efficiency (CGE) are parameters used to evaluate the gasification process. CCE reflects the percentage of carbon atoms of biomass that have been converted to syngas. However, CO_2 is one of the carbon-containing components of syngas that have no heating value. Thus, the performance of the gasification process can be better explained using cold gas efficiency, which represents the total energy of biomass that has been transferred to the syngas. As shown in Table 3, increasing trends were observed for CGE and CCE as the SCR increased up to only a certain flow rate. However, a further increase in steam flow rate resulted in a decrease in the mentioned parameters, similar to the results of Lv et al. (2004) and Salami and Skala (2015). CGE had peaked at SCR 0.6 with a value of 47.50%—the same peak SCR in terms of syngas HHV (5.28 MJ Nm^{-3})—while CCE peaked at SCR 0.9 with 75.49%.

Air Gasification vs Air-steam Gasification of Coconut Shells

The effects of air (SCR 0) and air-steam (SCR 0.6) as gasifying agents for coconut shells were analyzed in terms of the resulting syngas quality, CO_2 emission, and energy recovery.

Syngas Quality

The quality of the syngas produced from air and air-steam gasification of coconut shells is shown in Table 4. Results revealed that the syngas produced from air-steam gasification had less CO but more CH_4 due to WGS and methanation reactions. In terms of H_2 content, H_2/CO, and CH_4, results showed a statistically significant increase favoring air-steam gasification. Moreover, the heating value of syngas improved from 4.95 to 5.41 MJ Nm^{-3}. As for the measures of gasification performance, CGE increased from 47.99 − 51.01% while the CCE also increased from 77.64 − 81.75%. Hence, mixing steam with air as gasifying agent improves the quality of the resulting syngas.

Carbon Dioxide Emission

According to Cole and McCarthy (2014), the concentration of CO_2 in the atmosphere has been increasing since 1950 from a 134-year record, which is mainly due to the burning of fuels. Because of this, clean energy in the form of renewables has become the interest

Table 3. The gasification efficiencies and syngas HHV at different SCR.

Parameters	Steam-to-Carbon Ratio, SCR				
	0	0.3	0.6	0.9	1.2
Steam flow rate, kg h^{-1}	0.00	0.65	1.30	1.95	2.60
Gas yield, Nm3 $kg_{biomass}^{-1}$	1.44	1.50	1.44	1.44	1.44
CGE, %	43.53	45.27	47.50	44.92	44.77
CCE, %	72.92	74.75	74.87	75.49	71.38
HHV, MJ Nm^{-3}	5.13	5.16	5.28	5.02	5.04

Table 4. Syngas quality of air and air-steam gasification of coconut shells.

	Air Gasification	Air-steam Gasification	*p*-Value
	(SCR 0)	(SCR 0.6)	
H_2, $\%_{v/v}$	4.70	5.82	0.00216
CO, $\%_{v/v}$	15.63	14.97	0.50001
H_2/CO	0.30	0.39	0.00277
CO_2, $\%_{v/v}$	18.99	18.78	0.77863
CH_4, $\%_{v/v}$	3.53	4.38	0.04025
CGE, %	47.99	51.01	0.1749
CCE, %	77.64	81.75	0.15896
HHV, MJ Nm^{-3}	4.95	5.41	0.13137

of many researchers. Although biomass has carbon neutrality, different thermal conversion process produces varying degrees of CO_2 emissions. Therefore, the CO_2 emissions between air and air-steam gasification of coconut shells were analyzed.

Table 5 shows that air gasification yielded a total of 13.85 $CO_{2\ mol}$ $kg_{biomass}^{-1}$ while air-steam gasification had a slightly lower CO_2 production (13.42 $CO_{2\ mol}$ $kg_{biomass}^{-1}$). The relative change of CO_2 emission between air and air-steam gasification was the result of water-gas (WG) and water-gas shift (WGS) reactions.

Since WG drives the reaction of carbon and steam more actively in air-steam gasification, the improvement of carbon conversion results in less char yield. Air gasification yielded more char (191.2g) compared to air-steam gasification (167.9g). Hence, CO_2 emission from combusted chars derived from air gasification was observed to be higher (2.17 $CO_{2\ mol}$ $kg_{biomass}^{-1}$) compared to that of air-steam gasification (2.01 $CO_{2\ mol}$ $kg_{biomass}^{-1}$).

Energy Balance

The energy recoveries of the fluidized bed gasification process of coconut shells using air and air-steam as gasifying agents are presented in Fig. 4. The combined energy recovery from the syngas and chars was higher in air-steam (49.67%) than in air gasification (48.12%).

Higher energy recovery was observed from the chars of air gasification (8.90%) than air-steam (6.81%). This result supports the determined CCE values, where air gasification at SCR 0 was lower (77.64%) compared to air-steam gasification at SCR 0.6 (81.75%). More carbon left in the chars results in lower CCE and, consequently, higher char production.

Table 5. CO_2 emission of air and air-steam gasification of coconut shells.

Components	Air Gasific $CO_{2\ mol}$ $kg_{biomass}^{-1}$	Air-steam Gasification $CO_{2\ mol}$ $kg_{biomass}^{-1}$
Syngas	11.68	11.41
Char	2.17	2.01
Total	13.85	13.42

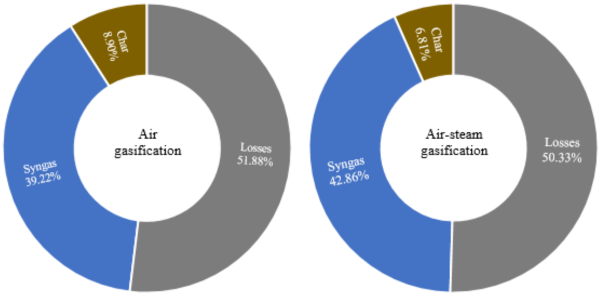

Fig. 4. Energy recoveries from air and air-steam gasification of coconut shell.

The study also found that a higher syngas recovery was observed in air-steam (42.86%) than in air gasification (39.22%). This result conforms with the higher CGE observed in air-steam gasification at SCR 0.6 (51.01%) compared to air gasification (47.99%), which means that more energy from the raw coconut shell was converted to syngas.

Similar to the study of Maguyon and Capareda (2013), the energy losses in this study accounted for the formation of noncombustible substances like H_2O and CO_2 as well as products that were not collected such as chars mixed in the bed materials and tars that adhered and condensed to the heat surfaces of the gasifier.

CONCLUSION

The effects of using air and air-steam as gasifying agents for the fluidized bed gasification of coconut shells were studied. When compared to the conventional air gasification at 700°C bed temperature and 0.25 ER, the use of air-steam significantly increased the syngas quality in terms of %H_2, H_2/CO, and %CH_4, produced less CO_2 emission, and exhibited higher energy recovery. Moreover, the study determined the optimum SCR at 0.6 based on %H_2 content, H_2/CO, CO/CO_2, HHV, and CGE. The study proved that mixing steam with the conventional gasifying agent up to an optimum SCR can significantly improve the gasification process and its outputs. These results can serve as a reference for coconut and biomass energy conversion industries that are focused on producing quality syngas with better energy recovery. For future studies on the air-steam gasification of coconut shells, exploring the effect of higher operating temperatures at different SCRs is recommended as this will promote endothermic reactions.

ACKNOWLEDGMENT

The authors are thankful to the Engineering Research and Development for Technology (ERDT) scholarship program of the Department of Science and Technology (DOST) and to the Bio-Energy Testing and Analysis (BETA) Laboratory of the Texas A&M University, USA.

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