Downdraft Gasification of Raw and Torrefied Palm Kernel Shell

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***Abstract*— Downdraft gasification is a potential method to produce biomass-based power suited for small-scaled power generation application. In the present study, a downdraft gasifier is used to gasify both raw and torrefied palm kernel shell (PKS). The properties of the palm kernel shells were characterised prior to gasification. Torrefaction of PKS was performed at the maximum temperature of 400 ^{o}C. Torrefied PKS shows lower moisture content by 4.8% as compared to raw kernel shell. Gasification of the feedstock showed that torrefied PKS produced higher amount of reactive syngas components, notably 16.4% CO and 9.25% H_2 (by volume) than its raw counterpart. The total lower heating value of the syngas produced by torrefied PKS is 7.2 MJ/kg higher than that of raw PKS. Comparison of the temperature profiles within the gasifier for torrefied and raw PKS show distinct differences, with the temperature of the oxidation zone for raw and torrefied PKS being 1115^{o}C and 1138^{o}C at the equivalence ratio of 0.41 and 0.30, respectively. Although both feedstock show high potential for synthesis gas production, torrefied PKS produces syngas of higher LHV.**

Keywords*— Downdraft gasification, Biomass, Torrefaction, Syngas, Palm kernel shell

I. INTRODUCTION

Gasification is one of the potential thermochemical conversion technologies that converts biomass into combustible gaseous fuels through partial oxidation processes [1-3]. Combustible gases known as producer gas or synthesis gas (syngas) consists of gases such as carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2) and nitrogen (N_2) [4]. The generated syngas can either be combusted as gaseous fuel for heat and electricity generation or processed further for downstream applications such as production of liquid transportation fuel [5, 6].

Gasification is carried out through a variety of gasification reactors. The gasification reactor can be classified into three main types; fixed bed, fluidised bed and entrained flow [7]. Present studies primarily focus on small-scaled gasifier applications, mainly targeting rural area where raw materials are abundantly available for feedstock. A fixed bed gasifier is typically classified into two different types; namely updraft and downdraft [2, 7]. Updraft gasifier products are not suitable for engines and gas turbines as the gas contains high level of tar (up to 150 g/m^3) [8]. Downdraft gasifier is more suitable for production of syngas for engine applications due to their low tar content (0.015-0.05 g/m^3) and particulates in the gasified products [9, 10].

The downdraft gasifier design generally incorporates a throat area. According to Bhavanam et al. [11], the throat promotes mixing of gases in the high temperature region which aids tar cracking. However, the throated area is less suited for biomass with considerably high moisture content (>25%) [12]. Additionally, the heating value of the gas produced from the downdraft method is lower than those produced by updraft method [13]. Therefore, the pre-treatment process of raw biomass is crucial in improving the properties and the operational efficiency of the former. Torrefaction has been shown effective

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in improving the properties of raw biomass [14]. Kuo et al. [3] reported that torrefied biomass is characterised by lower moisture, higher energy density and improved ignitability, reactivity and grindability when compared to untorrefied biomass. The improved properties of torrefied biomass include the increase of fuel heating value [3, 14].

Previous studies of downdraft gasifiers involved gasification using different types of biomass including untreated and treated biomass. Singh and Sekhar [10] conducted a gasification experiment using blends of rubber seeds shell and coconut shell in a downdraft gasifier. Results showed that gasification of mixed shells yields comparable performance as wood biomass. Olgun et al. [12] used wood chips and hazelnut shells as feedstock and found that an equivalence ratio of 0.35 produced the highest heat release of product gas for both biomasses. Balu and Chung [15] evaluated four different types of feedstock, namely pine wood, horse manure, red oak, and cardboard. It is worth noting that the gasification research focused mainly on untreated biomass. This is not surprising considering that considerable cost is involved in raw biomass pre-treatment processing. Kuo et al. [3] compared the thermodynamic and gasification performance of raw bamboo with torrefied bamboo at torrefaction temperatures of 200 ^{o}C and 350 ^{o}C. The analyses showed that higher torrefaction temperature results in higher syngas yield.

Due to the potential of palm kernel shell as renewable energy source and the lack of study on downdraft gasifier using the former, the present work focuses on the gasification performance of both torrefied and raw palm kernel shells at different equivalence ratios. The composition of the product gases are quantified and the lower heating value (LHV) of the gases are compared.

II. EXPERIMENTAL

A. Biomass materials properties

The raw palm kernel shell (R-PKS) and torrefied palm kernel shell (T-PKS) used in this study are shown in Fig. 1. The torrefied biomass was heated up in a furnace via a screw conveyor heating unit at temperatures around 400 ^{o}C to 500 ^{o}C. The screw feeding conveyor was set to rotate at the speed of 3600 rpm (50 Hz) for uniform and continuous process of homogenous heating for 3 – 6 hours, similar to those conditions reported in [16]. All biomass properties were characterised through proximate and ultimate analyses. Proximate analysis was performed by using a Thermogravimetric analyser (Perkin Elmer TGA7) to characterise the compositions of fixed carbon, volatile matter and ash content. An ultimate analysis was conducted using a CHNS/O analyser (Perkin Elmer 2400) to obtain the elemental composition of carbon (C), hydrogen (H), nitrogen (N), oxygen (O) and sulphur (S) in the sample. Table 1 shows the result of both proximate and ultimate analyses for all type of biomasses used in this study. Torrefied PKS shows higher C content, fixed carbon and HHV values by 23.2 %, 30.2 % and 9.2 MJ/kg respectively, as compared to raw PKS. Raw PKS shows higher moisture content, volatile matter and H content by 4.8%, 27.9% and 1.2% respectively compared to torrefied PKS.

B. Gasification reactor

The schematic of the present gasification system is shown in Fig. 2. The setup consists of a bench scale downdraft fixed bed gasification system, scrubber with cyclone separator and air supply. The gasifier is a cylindrical reactor comprised of four reaction zones, notably drying, pyrolysis, oxidation and reduction zones as shown in Fig. 3. The diameter and height of the reactor for drying and pyrolysis zones are 366 mm and 810 mm respectively. The gasifier is throated at the oxidation zone with the throat height and diameter of 232.5 mm and 101.6 mm respectively. The diameter and height of reduction zone is 300 mm and 210 mm. A perforated, cast iron grate is installed at the bottom of the gasifier to dispose the ash continuously from the bed. The gasifier was operated at atmospheric pressure for all test cases. During the gasification process, the gas produced from the gasifier entered the cyclone separator unit. The ash and chars in the hot gas are separated and collected in this section. Syngas produced after passing through the cyclone unit is then divided into two streams. One of the gas streams is directed to be flared while the other gas stream is passed through the sampling unit system.

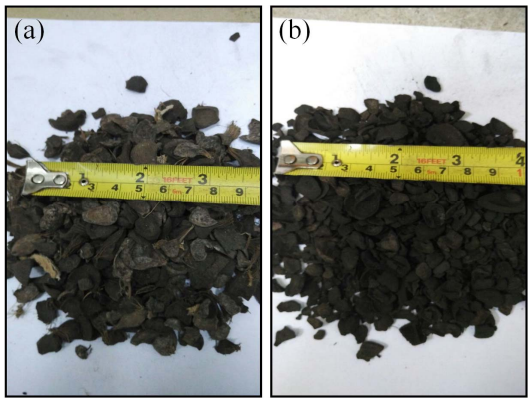

Fig. 1 Biomass feedstock of (a) raw PKS (b) and torrefied PKS

TABLE I. PROPERTIES FOR RAW AND TORREFIED PKS

Items	Raw PKS	Torrefied PKS
Moisture content, %	7.4	2.6
Proximate analysis		
Volatile matter, %	73.3	45.4
Fixed Carbon, %	19.3	49.5
Ash, %	7.0	2.6
Ultimate Analysis		
C, % wt	50.6	73.8
H, % wt	5.5	4.3
N, % wt	0.2	0.8
S, % wt	0.1	0.4
O, % wt	43.5	20.7
HHV [MJ/kg]	19.5	28.7

C. Operating conditions

The chemical formula of biomass is calculated to provide the stoichiometric air required for biomass gasification in the oxidation zone. The general stoichiometric equation for biomass is:

$$CH_wO_xN_yS_z + a(O_2+3.76N_2) \rightarrow CO_2 + bH_2O + zSO_2 + 3.76aN_2 \quad (1)$$

Table II shows the air flow rate supplied during the gasification process to establish the equivalence ratio range of 0.15-0.5. The mass of the PKS supplied is fixed at 5 kg for all test cases.

TABLE II. AIR FLOW RATE SUPPLIED FOR GASIFICATION OF PKS

Biomass type	**Air mass flowrate [kg/h]**				
	Run 1	*Run 2*	*Run 3*	*Run 4*	*Run 5*
Raw PKS	23.7	35.5	47.4	59.2	71.0
Torrefied PKS	23.7	35.5	47.4	59.2	71.0

D. Sampling of gases

The gas sampling train shown in Fig. 2 utilises an isokinetic gas sampling process which consists of a solid filtration unit and tar absorption in a solvent contained in a glass impinger. The glass impingers or bottles are placed within the cold water to keep the system at low temperature. The impingers require six glass bottles connected in series. The first impinger is left empty for moisture collection. The next four impingers are filled with isopropanol to condense the water and tar from the flowing gas of the gasifier. The last impinger is filled with silica gel for moisture removal and dehumidification of the gas stream. A peristaltic pump is used to extract the produced gas from the gasifier. The clean and dried gas that exits the sampling train is collected in a Tedlar gas sampling bag for analysis by a gas chromatograph (GC- Agilent 7890B) running on a thermal conductivity detector (TCD). The initial temperature of the oven was set at 60°C and gradually increases to 200°C, with the setup of the front detector temperature was set at 250°C. The GC was calibrated with standard calibration gases.

E. Measuring system

The temperature distribution along the reactor were measured by using 5 thermocouples (K-type) installed vertically along the centre of the reactor. The measured zones are drying (T1), pyrolysis (T2 and T3) , oxidation (T4) and reduction zone (T5) at 200 mm, 400 mm, 600 mm, 810 mm from the top to bottom of reactor respectively (Fig. 3). The clean, cooled and dried gas was sampled by a gas sampling bag at 5 minutes interval. Then, the main gas composition such as H_2, CO, CO_2 and CH_4 was analysed by a gas chromatography (GC- Agilent 7890B) coupled with a thermal conductivity detector (TCD), installed with 4 different columns (Agilent 0.5M 1/8 2mm HayeSep Q 80/100SS, Agilent 6ft 1/8 2mm HayaSep Q 80/100, Agilent 3ft Hayasep Q 80/100SS and Agilent Molsieve 5A 60/80SS).

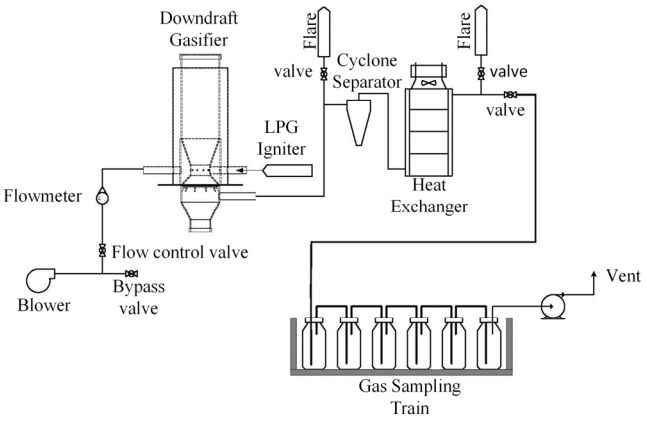

Fig. 2 Downdraft gasifier and gas sampling train system

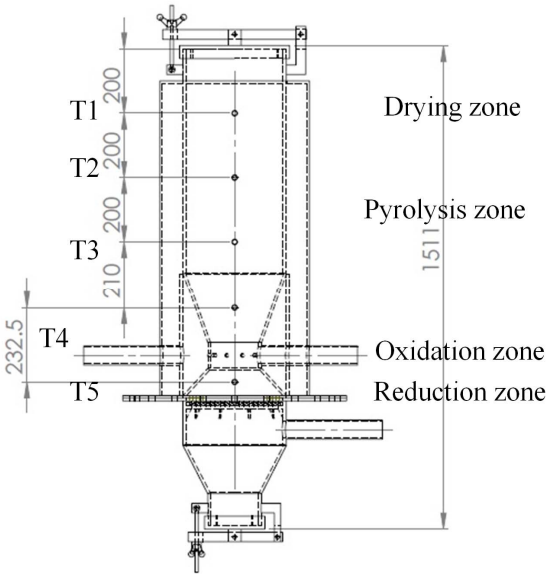

Fig. 3 Dimension of downdraft reactor, dimensions are in milimeter.

F. Operating procedure

Prior to the start of each experiment, 5 kg of biomass were loaded into the reactor. The burning process was ignited by using solid fuels such as coal and biomass fibre. Air was supplied to the bottom of the reactor which was controlled by an air blower. The air flow rate was measured by a flow meter controller. Sampling of the gas was conducted when the throat temperature of the reactor reached 700 – 800 ^oC after 30 minutes. During each test, the air flow rate was adjusted according to the required equivalence ratio by controlling the open valve of the air blower.

When the gasification process reaches steady state conditions, at which the temperature in the partial oxidation zone and the reduction zone are approximately constant, the gas produced was sampled in the sampling unit and the temperature distribution was recorded.

III. Result and Discussion

A. Analysis of both raw and torrefied biomass

Figure 4 shows the concentration of CO, H_2, CO_2 and CH_4 of the gas. Generally, gasification at low equivalence ratios causes the biomass reaction to approach pyrolysis conditions, whereas high equivalence ratio will approach combustion condition [3]. Detailed understanding on this reaction could be explained by Fig. 5. All tests were conducted within the equivalence ratio range of 0.15 to 0.5.

For raw PKS, reactive (CO, H_2 and CH_4) and inert gas (CO_2) components increase with the rise of equivalence ratio from 0.15 to 0.35. The increase in the amount of air rises the production of CO_2 and H_2O in the combustion zone. The high amount of CO_2 and H_2O in the combustion zone will in turn increase the amount of CO and H_2 production in the gasification zone through the Bouduard and water gas reactions. Methanation reaction is favoured as the amount of H_2 increases, hence the production of CH_4 is increased.

However, the trend is opposite for equivalence ratios of 0.35 to 0.45, at which CO, H_2 and CH_4 were slightly decreased while CO_2 increased. The increase of CO_2 and decrease of reactive component at this equivalence ratio condition denoted that CO_2 produced in the combustion zone is in excess to that of the conversion capacity of the reduction zone. At equivalence ratios between 0.43 to 0.51, both reactive and inert gas components were reducing, indicating that the amount of biomass fuel was almost completely burned to ash.

For torrefied PKS, it is observed that the concentrations of CO and H_2 were higher than for raw PKS at equivalence ratios (ER) of 0.15-0.38. High concentration of CO was due to the high carbon content (C component) in the torrefied PKS (73.8 %wt). The high H_2 production by torrefied PKS was likely due to the completion of the water gas reaction to water gas-shift reaction. As the process moved to water-gas shift reaction, high CO component which corresponds to high content of carbon (C) produced from water gas reaction increased the production of H_2. However, in raw PKS, the available C and CO component for reaction with H_2O to produce H_2 are lower compared to torrefied PKS.

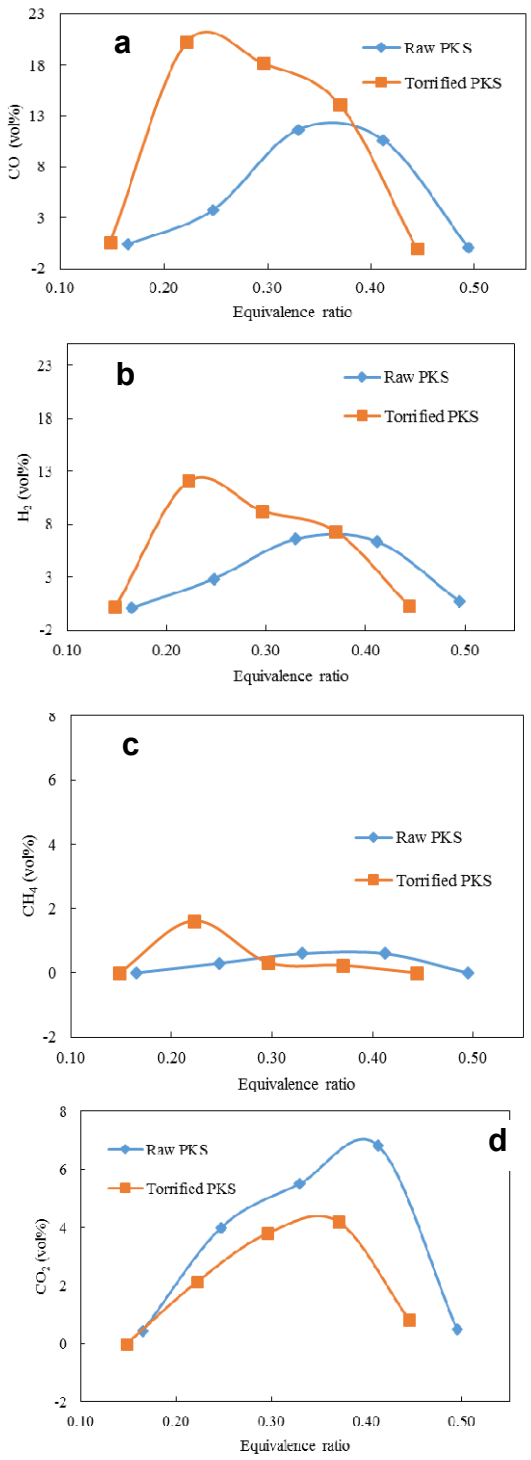

Fig. 4. (a) CO, (b) H_2, (c) CH_4 and (d) CO_2 constituents in syngas produced by gasification of raw and torrefied PKS.

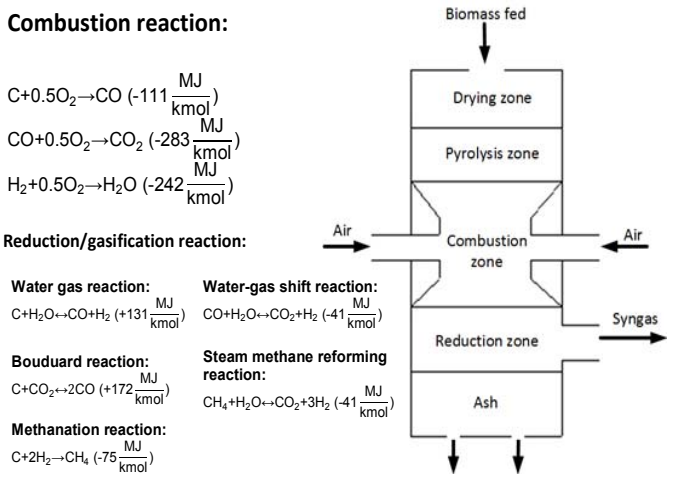

Fig. 5. Chemical kinetic reaction of gasification in downdraft reactor [13]

A sharp decline of CH_4 component above 0.2 ER was observed for torrefied PKS. Since combustion reaction is favoured at ER values, H_2 is hence more prone to production of H_2O rather than CH_4. Limited access of C components also contribute to the reduction of CH_4 production from the methanation reaction.

The quantity of CO_2 produced by torrefied PKS was lower compared to that of raw PKS. Apart from air supply, oxygen was also produced from H_2O. Since torrefied PKS has lower content of H_2O than the raw PKS, reaction towards more CO is favourable rather than completion to CO_2 formation due to lower amount of available oxygen [17].

Torrefied PKS was observed to peak at 0.23 ER while raw PKS peaks at 0.38 for CO, H_2 and CH_4 component. The slow increment of gases in the raw PKS was due to the high moisture content. High moisture content reduces the reaction temperature. Therefore, the dual-effect of low ER and high moisture causes the temperature to further reduce and hence decrease overall reactions of the gasification process for the raw PKS.

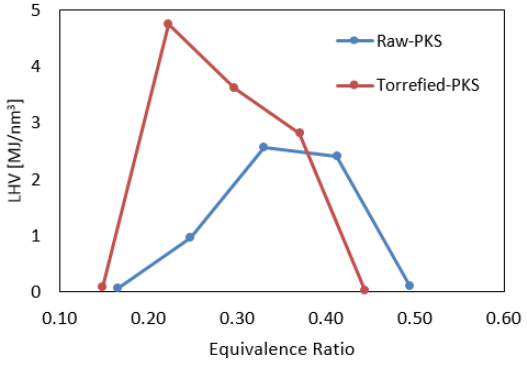

Fig. 6 LHV value of syngas produced by raw and torrefied PKS

B. Lower heating value (LHV) and temperature distribution

The lower heating value (LHV) for syngases produced for both feedstocks is shown in Fig. 6. Syngas produced from torrefied PKS shows significant higher LHV value than the syngas produced from raw PKS for ER between 0.23 and 0.38. The higher LHV value for torrefied PKS is due to higher reactive gas and lower inert gas components as compared to raw PKS. However, at the higher ER between 0.45-0.55, torrefied PKS shows a lower LHV value than that of raw PKS. In that region, the slightly higher H_2 content produced by raw PKS increases the LHV value.

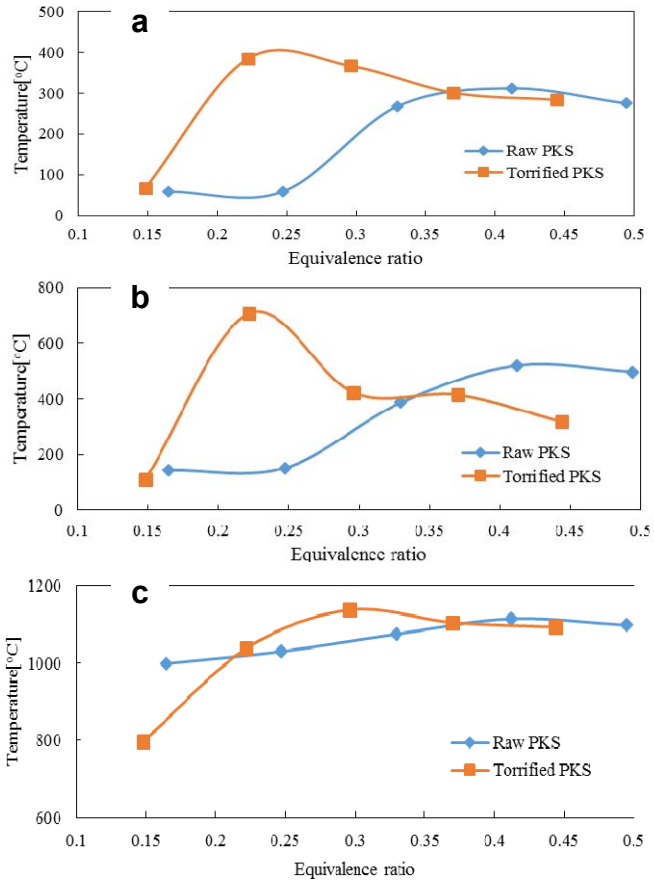

Fig. 7. Temperature distribution at different ER value in (a) drying, (b) pyrolysis and (c) oxidation zone of the reactor for gasification of raw and torrefied PKS.

Since raw PKS contains high moisture, production of H_2 is maintained through the exothermic reaction of water-gas-shift and steam methane-reforming-reaction. Torrefied PKS shows a general decrease of LHV values as ER increases. Higher ER causes the increment of oxidiser and completion of reaction which produce CO_2 and H_2O. As the production of inert components increase, the reactive component decreases and hence lowers the LHV.

Figure 7 shows the temperature distribution of the gasifier reactor at different ERs. For raw PKS, the temperature is observed to gradually increase with ER. The increase of O_2 concentration which corresponds to the increase of ER value causes the exothermic combustion reaction to occur and hence the increase of energy release [2]. At around 0.4-0.5 ER, the oxidation temperature for raw PKS begins to level, indicating the optimum ER that corresponds to the maximum production of CO and H_2. Gasification of torrefied PKS shows CO and H_2 production peaks at ER~0.2-0.3, where the pyrolysis and oxidation temperature in the reactor is the highest. The reactivity of the biomass is directly related to the temperature of the reactor. Reactive biomass leads to higher reacting temperature and more syngas production. Conversely, a less reactive fuel results in more N_2-diluted product gas and lower reaction temperature in the reactor [18]. In the present case, higher temperature was recorded for torrefied PKS in all three zones, signifying higher biomass reactivity due to higher carbon and low moisture content. Raw PKS shows lower temperature at ER <0.35 for both the drying and pyrolysis zones due to the presence of moisture in the feedstock that absorbs heat. Higher ER leads to higher reactivity rates for raw PKS.

IV Conclusion

Downdraft gasification of raw and torrefied palm kernel shells is investigated in the present study. The syngases produced from both feedstock were characterised. Torrefied PKS shows higher volume of reactive components of CO and H_2 produced compared to raw PKS biomass, leading to higher LHV of the syngas for the former. The high reactivity of biomass corresponds to high temperature of the oxidation zone in the reactor at certain air/fuel ratios.

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References

[1] P.N. Sheth and B.V. Babu, "Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier," Bioresource Tech vol. 100, pp. 3127-3133, 2009

[2] C. Gai and Y. Dong, "Experimental study on non-woody biomass gasification in a downdraft gasifier," Intl. J. Hydrogen Energy vol. 37, pp. 4935-4944, 2012

[3] P. Kuo, W. Wu, and W. Chen, "Gasification performances of raw and torrefied biomass in a downdraft fixed bed gasifier using thermodynamic analysis," Fuel vol. 117, pp. 1231–1241, 2014

[4] N.A. Samiran, J. Ng, M.A. Mohd Jaafar, A. Valera-Medina, and C.T. Chong, "H2-rich syngas strategy to reduce NOx and CO emissions and improve stability limits under premixed swirl combustion mode," Intl. J. Hydrogen Energy vol. 41, pp. 19243-19255, 2016

[5] D. Xu and R.S. Lewis, "Syngas fermentation to biofuels: Effects of ammonia impurity in raw syngas on hydrogenase activity," Biomass and Bioenergy vol. 45, pp. 303–310, 2012

[6] Z.A. Zainal Alauddin, P. Lahijani, M. Mohammadi, and A.R. Mohamed, "Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review," Renew. and Sus. Energy Rev. vol. 14, pp. 2852–2862, 2010

[7] N.A. Samiran, M.A. Mohd Jaafar, J. Ng, S.S. Lam, and C.T. Chong, "Progress in biomass gasification technique - with focus on Malaysian palm biomass for syngas production," Renewable and Sustainable Energy Reviews vol. 62, pp. 1047-1062, 2016

[8] C. Mandl, I. Obernberger, and I.R. Scharler, "Characterisation of fuel bound nitrogen in the gasification process and the staged combustion of producer gas from the updraft gasification of softwood pellets," Biomass and Bioenergy vol. 35, pp. 4595–4604, 2011

[9] J. Nisamaneenate, D. Atong, P. Sornkade, and V. Sricharoenchaikul, "Fuel gas production from peanut shell waste using a modular downdraft gasifier with the thermal integrated unit," Renew Energy vol. 79, pp. 45- 50, 2015

[10] V.C.J. Singh and S.J. Sekhar, "Performance studies on a downdraft biomass gasifier with blends of coconut shell and rubber seed shell as feedstock," Appl. Thermal Eng. vol. 97, pp. 22-27, 2016

[11] A. Bhavanam and R.C. Sastry, "Biomass Gasification processes in downdraft fixed bed reactors: a review," Intl. J. Chem Eng. Application vol. 2, pp. 425-433, 2011

[12] H. Olgun, S. Ozdogan, and G. Yinesor, "Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues," Biomass and Bioenergy vol. 35, pp. 572-580, 2011

[13] P. Basu, "Biomass Gasification, Pyrolysis and Torrefaction (Second Edition): Practical Design and Theory," Academic Press vol., 2013

[14] D. Tapasvi, R.S. Kempegowda, K. Tran, Ø. Skreiberg, and M. Grønli, "A simulation study on the torrefied biomass gasification," Energy Manage Converse vol. 90, pp. 446–457, 2015

[15] E. Balu and J.N. Chung, "System characteristics and performance evaluation of a trailer-scale downdraft gasifier with different feedstock," Bioresource Tech vol. 108, pp. 264-273, 2012

[16] M.F. Hamid, M.Y. Idroas, M.Z. Ishak, Z.A. Zainal Alauddin, M.A. Miskam, and M.K. Abdullah, "An Experimental Study of Briquetting Process of Torrefied Rubber Seed Kernel and Palm Oil Shell," BioMed Research Intl. vol. 2016, pp. 1679734:1-11, 2016

[17] M. Strandberg, "From torrefaction to gasification: Pilot scale studies for upgrading of biomass," Department of Applied Physics and Electronics, Doctoral Thesis, Umeå University, Sweden vol. pp. 2015

[18] C. Erlich and T.H. Fransson, "Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental study," Appl. Energy vol. 88, pp. 899–908, 2011