An Experimental Investigation of Syngas Composition from Small-Scale Biomass Gasification

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Abstract

The proposed study is to evaluate the performance of a modular biomass gasification to produce syngas for the purpose of utilizing as supplementary source for power generation application. Experiments were carried out in two different-scale reactors (a 1Kw-fluidized bed cylindrical gasifier, 370mm height and 54mm of diameter and a 5Kw self-sustaining fluidized bed gasifier, 700mm height and 127mm diameter) at different temperatures and equivalent ratios (ER). The selected biomass is palletized Napier grass to be used as the feedstock for both reactors. The result data shows an increasing yield in syngas ($CO + H_2$) by increasing the temperature. Furthermore, it shows that an ER of 0.2 is best performing. Apart from retrieving high syngas yields, an ER of 0.2 also showed to have the least oil production and the most heating value and carbon conversion which is desirable for a gasification process. Once with the optimum ER and the maximum yield of syngas, gasification efficiency and therefore the potential of its energy generation is expected to meet the prospects.

Keyword : Napier grass, gasifier, equivalent ratio, gasification efficiency

1. Introduction

Biomass gasification can be the key in turning underutilized biomass into clean and sustainable energy, having several benefits over traditional sources of electricity (Mustafa et al., 2015).

Thermochemical biomass gasification is a recognized technology and has been developed for variety of industrial applications. The conversion of biomass into hydrogen-rich gas seems to be a suitable source for energy production regarding its advantages e.g. renewable energy, sustainability, environmental friendly characters such as low amount of CO_2 emissions etc.

Since the chosen self-sustaining reactor for this study is meant to be as possibly economic and user friendly therefore the focus is to select the most efficient design and process with least of expenses and to avoid advanced and sophisticated technologies which probably increases the initial cost of implementation.

The producer gas quality in terms of composition and energy content, and moreover the gasification performance i.e. gas yield, are strongly dependent to feedstock origin, gasifier design and operating parameters.

The proposed study intends to utilize Napier grass as feedstock and perform a biomass gasification process using two types of small scale fluidized bed reactors, a 1kw electrically heated and a 5kw self-sustaining reactors. The operation process tends to improve through investigating the effect of different gasification parameters on the producer gas composition and the amount of gas yield. Modifying parameters are temperature and Equivalent ratio.

Plenty of tropical or subtropical crops have considerable biomass production yields. For instance, switch grass (Panicum virgatum) and Napier grass (Pennisetum purpureum) have broadly been regarded as potential energy sources. Napier grass, which is also called elephant grass can produce large yields of dry matter comparing to other biomass (Xie et al., 2010).

1.1. Feedstock Selection

Napier grass is chosen due to its high dry matter yielding capability and other favourable characteristics such as fast growth, disease resistance, adaptability, minimal management and easy propagation (Okaraonye & Ikewuchi, 2009). A record of proximate and ultimate analysis values for different variaties of biomass has been presented in table 1 showing that with relatively high amount of carbon content and volatile matter and adequately low moisture content, Napier grass is accurately comparable to other suitable biomass for gasification purposes.

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Table 1. Proximate/Ultimate analysis for a selection of biomass feedstock

Feedstock	Coconut husks	Napier Grass	Oil palm Frond	Palm kernel shell	Coconut shell	Empty fruit bunch
Author	(Adeyi, 2010)	-	(Wan Azlina et al., 2009)	(Wan Azlina et al., 2009)	(Wan Azlina et al., 2009)	(Abdullah et al., 2011)
Proximate analyses						
Moisture content	5.43	4.5	4.22	7.96	4.89	7.95
Volatile matter	71.30	85.52	83.38	72.47	30.62	83.86
Fixed carbon	15.2	8.17	11.88	18.56	26.41	10.78
Ash	3.95	6.33	4.84	8.97	42.98	5.36
Calorific Value (*10^{-3} Kcal/kg)	5.80	3.90	3.5-4	4	3.5-4	4.1-4.53
Ultimate analyses						
Carbon	40.6	45.10	45.05	51.63	45.24	46.62
Hydrogen	5.15	5.94	5.86	5.52	5.04	6.45
Nitrogen	1.83	0.45	0.23	1.89	1.46	1.21
Sulfur	0.09	0.00	0.04	0.05	0.06	0.035
Oxygen	36.02	48.52	48.82	40.91	48.2	45.66

kcal/kg = MJ/kg * 238.846

1.2. Challenges regarding the Scale-up in biomass gasification

Common challenges related to biomass gasification such as predicted high costs of commercializing, downstream processing, lower efficiency comparing to carbon-based sources along with the knowledge connected with syngas production from biomass have been always constrained the ambitions of scale-up from pilot plant. Technical challenges including tar elimination and gas cleaning operations, the steady production of gas which is free from impurities, and difficulties associated with providing the large amount of biomass as feedstock (consumption of around 4000kton/year for palm oil mill industries according to (PTM, 2009)) are involved. Although common challenges linked with each component of biomass gasification process have individually been solved on small scale, however the integration of these challenges has still poses a major barrier in scale up and commercializing (Qureshi, N. et al. 2014).

2. Experimental setups and methodology

The schematic diagrams of the experimental facilities used in this study is shown in *Figure 1* and *Figure 2*. Both gasifiers was specially designed for operation under atmospheric or pressurized conditions.

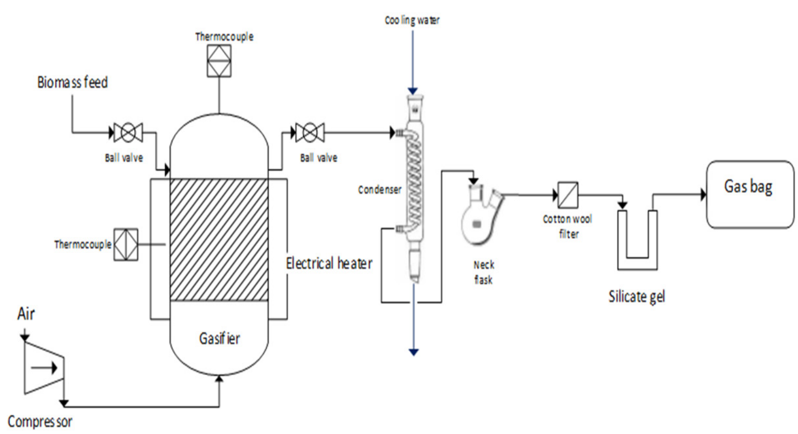

Figure 1 : Schematic diagram of biomass air gasification in 1 kW fluidized bed reactor

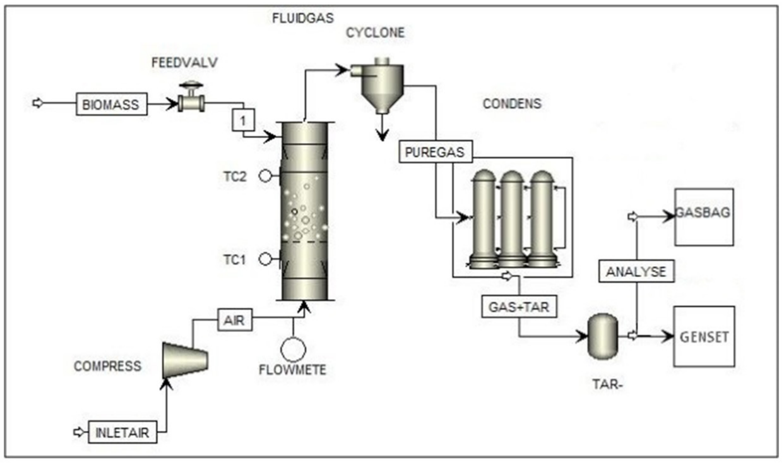

Figure 2 : Schematic diagram of biomass air gasification in 5 kW fluidized bed reactor

2.1. Biomass Characterization

Although potentially all types of biomass can be converted into energy, this research is focused on Napier grass as a feedstock. The crops for this proposed study has been provided from Crops For the Future (CFF) organisation, Semenyih, Malaysia. Crops For the Future Research Centre (CFFRC) was established in 2011 to provide research support for the global Crops For the Future organisation. In 2014, Crops for the Future and CFFRC combined their resources to form a single global entity as Crops For the Future (CFF).

The biomass has been pre-dried, crushed and palletized by the organization. The proximate and ultimate analyses of the feed stock has been conducted as reported in *Table 2*. The formula of Napier grass, $CH_{1.58}O_{0.81}$ was calculated from the ultimate analysis of biomass.

Table 2. proximate and ultimate analyses of Napier grass

Proximate Analysis (% by weight basis)	
Ash	6.31
Volatile matter	85.52
Fixed carbon	8.17
Ultimate Analysis (%by weight basis)	
Carbon	45.10
Hydrogen	5.94
Oxygen	48.52
Nitrogen	0.45
Sulphur	0.00
Moisture content (% by weight basis)	4.64
HHV (MJ/kg)	16.73

2.2. Experimental set-ups and procedures

The two individual designs of experiments for both reactors is described in details and the procedures to accomplish each experiment is discussed in following sections.

2.2.1. The small scale 1kW gasifier

The gasification of the palletized Napier grass with average size of 10 mm, was carried out in an electrically heated fluidized bed gasifier. The reactor having an internal diameter of 54 mm and height of 370 mm, was made of heat resistant stainless steel. To supply desired heat for start-up and also maintaining the heat loss and control during the operation, the reactor is surrounded by two individually controlled electric heaters and two K-type thermocouples has been installed across the reactor to ease the temperature controlling.

The reactor was filled with oven dried sand as a heating medium. The bottom of the reactor was connected to an air compressor with an air flow meter in between (*figure 1*). The continuous stream of ingoing air acted as a gasification agent. After the gas outlet of the reactor, a water cooled condenser was installed to cool the outgoing gas. The gas then flows through a twin-neck flask, to capture any created fluids (bio-oil), after which the gas was dried using silica gel and flew through a cotton wool filter to capture additional tar. From here the gas was fed into the gas analyser. The formed ash was captured inside the reactor, and the difference in weight of the sand before and after the experiment was used to determine the amount of ash formed.

The tests were performed at two temperatures which were 750°C and 800 °C, while air flow rate was varied from

15.9 to 24.38 L/min to maintain the ER values at 0.2 to 0.4 respectively. For each test the temperature controller and electric furnace heater were turned on to heat the reactor to desired temperature. At beginning of the experiment, the reactor was charged with 60 g of sand as bed material, which helped in stable fluidization and better heat transfer. After the bed temperature reached the desired level and remained steady, the air compressor was turned on to force air through the air distributor into the reactor. When the bed temperature became steady, Napier grass pellets were put into reactor every 3 minutes. The produced gases and fluid products were flowed out of the reactor and passed through a water condenser. Condensable gas turned into liquid-based oil and captured by filters while non-condensable gas was collected by gas-collecting bag for sampling after cleaning. Three samples were taken at an interval of 3 minutes. At the end of experiment any leftover char and water-based oil are removed from gasifier and weighed.

2.2.2. The small-scale 5kW self-sustaining gasifier

The gasification of the palletized Napier grass was carried out in a 5 kW bubbling fluidized bed gasifier with 700 mm height and with outer and inner diameters of 127 mm and 97 mm respectively. The reactor was filled with heating medium. (Mixture of sand, charcoal and biomass; preheated and pre dried). The bottom of the reactor was connected to an air compressor with an air flow meter in between (*figure 2*). After the gas outlet of the reactor, a cooling water condenser was installed to cool down the outgoing gas which then will flow through a twin-neck flask to capture any water-based fluids, after which the gas was decontaminated from tar and residual bio-oil by passing through fiber filter, it collected by gas bags (to prepare for GC-FID test) separately from each experiment.
The tests has been performed two times and in two temperature values of 750 °C, 800 °C with equivalent ratio of 0.2 within 40 minutes. Napier grass as feed stock with amount of 1kg has been specified for the experiments to be inserted into reactor by rate of 200 grams for every 8 minutes. Bed medium (consist of sand and charcoals) preheated to 600 °C prior to perform the experiments and the initial bed height has been set to 200mm (using 1.5kg of bed medium) above the air distributor at the bottom of the column. For each test the pre-heating of the reactor with the airflow rate of 300 cm^3/s was required to maintain the desire operation temperature.

After the bed temperature reached the desired level and remained steady, the air compressor was turned on to force air into the reactor. Airflow rate has been set to 150 L/min with the purpose of maintaining the ER value at 0.2. The producer gas after exiting from the gasifier and passed through condenser to get to the temperature of 27 °C, and cleaned from tar contaminants through filters, thus has been collected by gas-collecting bags for Gas chromatography sampling. All collected char and water-based oil from all steps are collected at the end of the experiments and weighed.

3. Results and Discussion

The results for the effect of Equivalent Ratio at the static amount of temperature, for the 1kw gasifier and for the effect of temperature at the static equivalence ratio for 5Kw gasifier has been presented and discussed in following sections.

3.1. Effect of Equivalence Ratio (ER) on syngas quality in 1kw small-scale gasifier

The effect of Equivalence Ratio on the quality of the producer gas was investigated for 0.2, 0.3 and 0.4 under the temperature of 800 ºC and 750°C. The CO_2 slightly declined and reached to 10.67 (vol.%) at ER of 0.4 compared to 11.84 (vol.%) at ER of 0.2 and 11.61 (vol.%) at ER of 0.3 (*figure 3*). This was same with that of the CO, which decreased from 6.73 (vol.%) at ER of 0.2 to 2.25 (vol.%) at ER of 0.4. By increasing ER from 0.2 to 0.4, H_2 decreased from 20.33 (vol.%) to 11.24 (vol.%) and CH_4 decreased from 9.37 (vol.%) to 3.03 (vol.%) respectively. In theoretical, as ER increases, it would provide higher quantity of oxygen contact with solid carbon together would accelerate the oxidation of carbon and could enhance the quality of syngas. But it is greatly depend on the feedstock input, the gasification performance would reduce as less feedstock input with high air flow of air. The carbon conversion efficiency were calculated from the gas compositions obtained by gas chromatography (GC). Carbon conversion efficiency were increased from ER of 0.2 to ER of 0.3 and then decreased with increasing ER. This could be due to the shorter residence time of solid particles as they entrained in the gas stream of which the velocity was proportional to the gasifier temperature. This relationship between equivalence ratio and carbon conversion efficiency have been observed in the other studied different types of systems and feedstock (Gomez-Barea et al., 2005; Lv et al., 2004). In addition, the highest gas velocity in the gasifier would carry the lower density of fly ash with the unburned carbon did not have enough residence time to further react either with O_2 for combustion or with CO_2 and H_2O for gasification and consequently a decrease in the carbon conversion efficiency was observed. As ER increases, the high heating value of syngas were decreases gradually from 7.17 to 2.92 MJ/Nm^3 as more incombustible gas species (CO_2 and N_2) were introduced to the gasifier and it is dilutes the synthesis gas and lower its heating value. The higher heating value is considered as chemical energy of product gas so it is directly affect the cold gas efficiency. The cold gas efficiency were decreased from 80.49 to 43.29%. In terms of gas yield, ER is an important parameter to determine the productivity of gasification. Increase in ER from 0.2 to 0.4, it caused the gas yield to rise from 1.878 to 2.480 N m^3/kg.

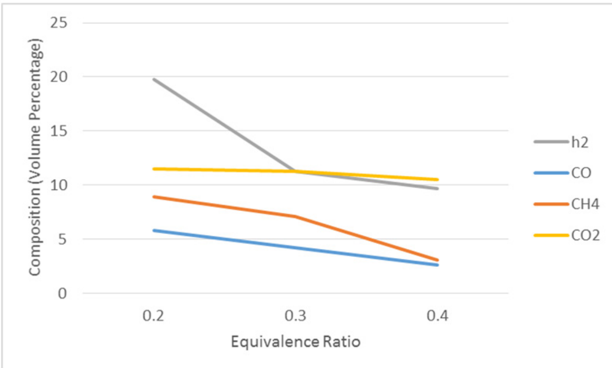

Figure 3 : The effect of Equivalence Ratio on gas compositions at 800°C in 1Kw gasifier

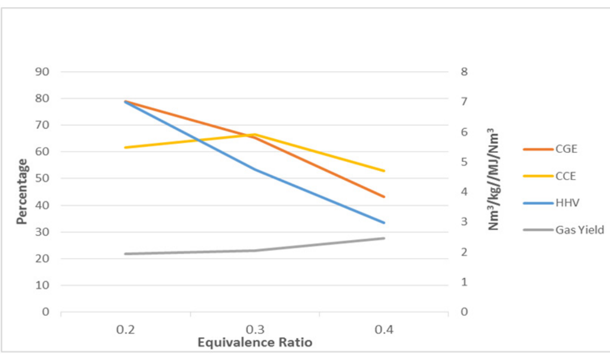

Figure 4 : The effect of Equivalence Ratio on carbon conversion efficiency, cold gas-efficiency, High heating value and gas yield in 1Kw gasifier

3.2. Effect of Temperature for (small scale 5kW reactor)

The effect of reactor temperatures of 750 °C and 800 °C on the producer gas composition has been investigated while the ER value is constant at 0.2 for both temperature sets. As shown in figure. 5 the amount of H_2 increases from 12.61 vol% at 750 °C to 18.12 vol% at 800 °C while CO is tend to decline to some extent from 7.21 vol% to 12.38 vol%. Higher temperature of 800 °C shows to effect the composition of CH_4 to slightly increase from 1.77 vol% to 1.86 vol %. This might be for the cause of higher energy provided from combustion reaction which tends to have a push-forward effect for methanation reaction in gasification zone. The amount of CO_2 in vol % doesn't showed to get much effected with the temperature rise, which is slightly changes from 11.75 vol % to 10.21%.

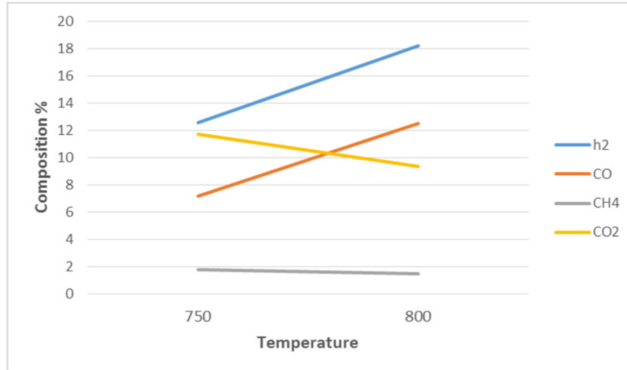

Figure 5 : The effect of temperature on Syngas composition in 5Kw gasifier

The effect of different temperatures on gasification efficiency parameters e.g. the cold gas efficiency (CGE), carbon conversion efficiency (CCE), higher heating value (HHV) and gas yield is illustrated in figure 6. Since the variation in HHV, CCE and CGE regarding to equations 1-4 are mostly depend on the syngas composition, hence both are increasing in respect to the raise in composition values (*figure 5*). Higher temperature results to higher char spilt fraction which means that more syngas is converted from bio-chars and thus the gas-yield increases respectively.

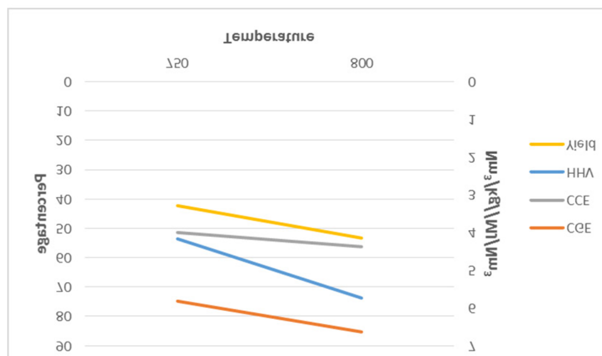

Figure 6 : The effect of temperature on carbon conversion efficiency, cold gas-efficiency, High heating value and gas yield in 5Kw gasifier

3.3. Comparison

In order to compare the results from the experiments conducted on both reactors, additional experiment on small-scale 1kw reactor has been conducted at 750°C and ER of 0.2 and the results are indicated in

Figures 7 and 8 along with other comparable values. Syngas composition results at 750°C prove a more efficient gasification for the smaller reactor since with higher values of H_2 and CO.

But adverse trend is observed in 800°C and shows higher syngas composition for 5kW reactor at this specific temperature.

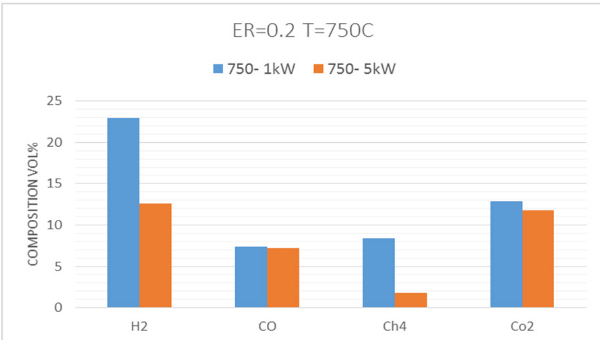

Figure 7 : Comparison of Syngas composition at 750°C for both reactors at equivalent ratio of 0.2

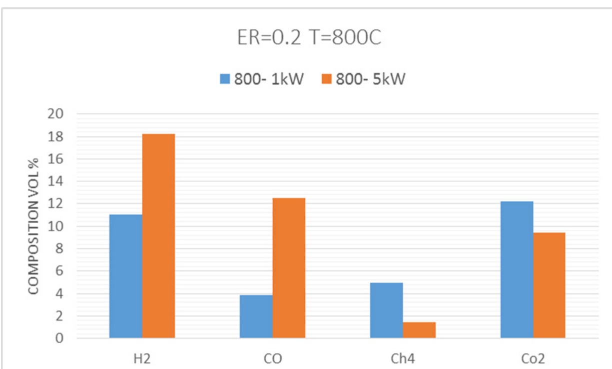

Figure 8 : Comparison of Syngas composition at 800°C for both reactors at equivalent ratio of 0.2

3.4. Calculating the gasifier efficiency and other related values.

The calculation of the producer gas heating value (in MJ/Nm³), dry gas yield and cold gas efficiency were performed by employing the Equations. 1 to 4 (Xiao et al., 2006) as shown below:

Higher heating value (HHV) of syngas produced,

$$HHV = (CO\% \times 3018 + H_2\% \times 3052 + CH_4\% \times 9500)(0.01 \times 4.1868)(KJ/Nm^3) \quad (1)$$

Where, $CO\%$, $H_2\%$ and $CH_4\%$ are the volumetric composition of the syngas produced, respectively.

The dry gas yield (Y) can be determined as:

$$Y = (Q_a \times 0.79)/(W_b(1 - X_{ash}) \times N_2\%)(Nm^3/kg) \quad (2)$$

Where, Q_a is the flow rate of air (Nm^3/h), W_b is the mass flow rate of feedstock (kg/h), X_{ash} is the ash content in the feedstock and N_2 % in the dry syngas.

Carbon conversion efficiency, nc % can be determined as: (Lv et al., 2004),

$$nc = Y(CO\% + CH_4\% + CO_2\%) \times 12)/(22.4 \times C\%) \times 100\% \quad (3)$$

Where, $CO\%$, CH_4 % and $CO_2\%$ are the volumetric compositions in the syngas, and $C\%$ is the carbon content of the feedstock by weight.

Cold gas efficiency is defined as the ratio of energy of the producer gas per kg of biomass to the HHV of the biomass material can be determined as:

$$\text{Cold gas efficiency} = (H_g)(Y)/(H_b) \quad (4)$$

Where, H_g (MJ/Nm^3) and H_b (MJ/kg) are the heating value of syngas and biomass, respectively.

The calculated values regarding the gasifiers performances at different process conditions along with the other data and achievements from the study has been listed and indicated in table 3.

Table 3. The calculated gasification efficiency values for both 1Kw and 5 Kw gasifiers under different temperatures and equivalence ratios.

Small-scale 1kw gasifier at 750°C

Equivalence Ratio	0.2	0.3	0.4
HHV	7	4.75	2.97
CGE	78.9	65.4	43.2
Gas Yield	1.94	2.05	2.45
CCE	61.65	66.4	53

Small-scale 5kw gasifier at equivalence ratio of 0.2

Temperature	750°C	800°C
HHV	4.18	5.75
CGE	74.9	85.4
Gas Yield	3.3	4.15
CCE	51.6	56.4

Note: HHV=higher heating value, CGE=Cold gas efficiency, CCE=carbon conversion efficiency

4. Conclusion

Air gasification of Napier grass has been performed in two different small-scale fluidized bed gasifiers and the effect of equivalent ratio and temperature has been evaluated on the producer gas quality. The results from Napier grass characterization, HHV of 16.73 (MJ/kg), volatile matter of 85.52 , carbon content of 8.17 and moisture content of 4.64, proves that Napier grass has the potential as high as comparable to other kinds of feedstock to be utilized in gasification process and energy conversion operations. The ER was found to have complex effects to the gas composition and gasification performances on 1 kW reactor as which by increasing ER from 0.2 to 0.4 the amount of H_2 declined so as CO and CH_4 but it seemed to have less effects on CO_2 composition. The ratio of HHV dropped by increasing ER value as well as cold gas efficiency, but the dry gas yield increased and there appears to have fluctuations on carbon conversion efficiency.

The syngas composition from 5kW gasifier experiments showed to be effected by increasing the temperature from 750°C to 800°C. The amount of hydrogen increased as well as CO and CH_4 while there was a slightly decline in the amount of and CO_2.

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