



EVALUATION OF THE EFFECTS OF LOCALLY SYNTHESIZED CATALYSTS AND TEMPERATURE ON GASIFICATION PRODUCTS DURING CO-GASIFICATION OF COAL AND BIOMASS

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Abstract - Electric power production for domestic and industrial applications enhances economic development and growth, but its sustainability is a big challenge. In this study, a blend of biomass and coal was gasified in a bench-scale fixed-bed gasifier to produce hydrogen-enriched syngas for electricity generation. The effects of two critical gasification parameters namely; catalyst and temperature on gasification products (syngas and tar) and gasification systems efficiencies were studied. The co-gasification test was carried out using Coal + Pine Sawdust (PSD) at temperatures of 700, 800, and 900 °C. Two operating process conditions namely; With Catalyst (WICAT) and Without Catalyst (WOCAT), were considered. The catalysts used are Pine Sawdust-Biochar (PSD-BC) and Nickel-Pine Sawdust-Biochar (Ni-PSD-BC) synthesized by the wet incipient impregnation method. The biochar used as catalyst and support was produced from PSD in a quartz tubular reactor using nitrogen as the inert gas. When Ni-PSD-BC and PSD-BC (WICAT) were used, the syngas yield was higher than that of WOCAT by 11.33 % and 5.82 %, respectively. Syngas yield at 900 °C was higher than that of 700 °C by 14.07 %. When the gasification temperature was increased from 700 to 900 °C, the H₂ and CO contents increased from 29.95 to 41.87 % and 19.45 to 25.18 %, respectively. The amount of tar in the product gas ranges from 8.01 – 12.96 g/Nm³ at 700 – 900 °C temperature conditions and 4.55 – 4.96 g/Nm³ when the PSD-BC and Ni-PSD-BC catalysts were used, respectively. The quality of gases produced at 700, 800, and 900 °C WOCAT are not suitable for use in fuel cells and gas turbines, while those produced at 900 °C WICAT, can be used in internal combustion engines and gas turbines, but unfortunately, have lower quality to be used in fuel cells for electricity production.

Keyword: Biochar; Biomass and Coal; Electricity; Fixed Bed Gasifier; Local Catalyst

1. Introduction

Syngas is one of the most important products of gasification or co-gasification process using fuels such as natural gas, biomass, coal, or a mixture of coal and biomass. The gas when produced can be used as fuel in fuel cells or gas turbines to generate electricity Wang et al. (2013). This fuel is attractive because it can burn in both fuel cells and gas turbines with little or no emission of dangerous gases against coal which pollutes the environment (Wang et al., (2013) and Akia et al., (2014). Also, when this gas is produced from biomass or agro-

waste and/or blends of biomass and coal, it generates lower amounts of carbon dioxide (CO₂), nitrous oxides (NO_x), Sulphur oxides (SO_x) when compared to solitary gasification of coal (Ozonoh et al., 2018). The level of emission of gases from the fuel used for the gasification process is dependent on the H₂-to-CO ratio. If the H₂-to-CO ratio is high, there will be low emission of dangerous gases, while high emission of gases occurs when the H₂-to-CO ratio is low (Akia et al., 2014). In this case, different experimental process conditions are combined to ensure lower emission of gases to

the environment.

Tar is also one of the major products of biomass or coal-biomass gasification, and is a complex mixture of aromatics containing a significant fraction of polycyclic aromatic hydrocarbons (PAH) (Lu et al., (2012) and Guo et al., (2009). It can cause blockages of valves, filters, condensers, and feed lines in the gasifier during the gasification process. Its presence in the syngas can also reduce the quality of the gas and the performance of the end-user equipment significantly (Iversen et al., 2006). According to Iversen et al., (2006), the allowable tar limit in syngas for gas engines, gas turbines, and fuel cells for energy production are 50, 5, and 1 mg/Nm³, respectively (Iversen et al., 2006). To ensure that the tar limit is not exceeded it will be necessary that different operating process conditions such as the type of fuel, use of catalyst, and temperature are considered. This will enable the enhancement of tar cracking and syngas yield as well as the other gasification efficiency parameters presented in the material and methods section of this paper. The application of catalyst and use of gasification temperature have been reported by Baskara et al., (2014). as one of the effective means of ensuring that a hydrogen enriched syngas is produced. The content of tar in the syngas can equally be minimized via the same conditions explained earlier.

It is important to point out that the techno-economic analysis of feedstock for energy generation (Ozonoh et al., 2018). and the theoretical evaluation of the gasification systems efficiency using Coal and Corn Cob (Coal + CC), Coal and Sugarcane Bagasse (Coal + SCB), and Coal + Pine Sawdust (Coal + PSD) were carried out in our previous researches (Ozonoh et al., 2020). From the studies, it was observed that Coal + PSD was the most viable feedstock in terms of profit-making and emission reduction.

However, co-gasification of coal and biomass has several benefits such as (1) reduction in tar production and cost of feedstock for energy generation (2) reduction in the fast depletion of coal due to its solitary gasification (3)

provision of an effective means of waste management (4) provision of sustainability in the energy production sector, hence; resulting in enhanced economic growth and development (Ozonoh et al., 2018). On this account, the fuel (Coal + PSD) is chosen for this study.

It is worth mentioning that a study on the use of a blend of high ash content South African coal (e.g. Matla Coal) and agro-waste (e.g. PSD) to determine the effects of catalyst and gasification temperature on gasification products and efficiency has not been reported in the literature. In this study therefore, Pine Sawdust-Biochar (PSD-BC) and Nickel-Pine Sawdust-Biochar (Ni-PSD-BC) catalysts and gasification temperature conditions of 700, 800, and 900 °C and residence time of 15 – 20 min were used for the co-gasification experiment and tar conversion process. The catalysts are waste-based and their effects on gasification products including syngas and tar content, and gasification efficiency (e.g. syngas yield and gas composition (quality), Lower Heating Value (LHV) of gas, carbon conversion efficiency, cold gas efficiency) were evaluated.

The study is relevant especially now that the South African Power sector is confronted with load shedding of electric power, hence, affecting consumers all over the country. Similarly, in sub-Sahara Africa such as Nigeria and Niger Republic, electric power generation and transmission pose huge challenges to the power sector, and electricity generation via a blend of waste biomass (which is abundant) and coal could help in alleviating the electricity production problem. In this regard, a method that will enhance electricity production in the country must be considered and well understood. The outcome of this study will provide an energy generation method that will be environmentally friendly, energy-efficient, and sustainable in all ramifications. This study will also be instrumental to using a high ash content South African coal such as Matla coal effectively for energy production by blending it with waste feedstock (e.g. PSD). Also in this

study, the Co-gasification of Coal + PSD will be instrumental to tar reduction as demonstrated in the volatile matter (VM) content of the blend that is displayed in Table 1. The study will equally provide an alternative method of waste management system in South Africa and sub-Saharan Africa since an agro-waste material (PSD) could be used as fuel, a precursor for biochar production, and as a catalyst in the gasification process.

2. Materials and methods

2.1. Materials

Coal and Pine sawdust (Coal + PSD) was the feedstock used for the co-gasification test. Some of the characterization analysis is shown in the results and discussion section of this paper, but detailed information about the feedstock origin, pre-treatment, and characterizations was reported in (Ozonoh et

al., (2018) and Ozonoh et al., (2020). From our previous research (Ozonoh et al., 2018), a coal-to-biomass ratio of 1:1 was reported as the most viable blend ratio, hence; it is used in this study for the gasification experiment.

2.2. Method

The method employed in this study is divided into four phases. It includes; (1) feedstock processing and characterization; (2) production of biochar from PSD; (3) catalyst synthesis and (4) co-gasification test. Phase 1 and Phase 4 are presented in this article. The research focus basically, is not on biochar production (phase 2) and catalyst synthesis (phase 3), but on the effects of temperature and biochar/synthesized catalyst on the gasification products. A schematic of the experimental facility used for the study is shown in Figure 1.

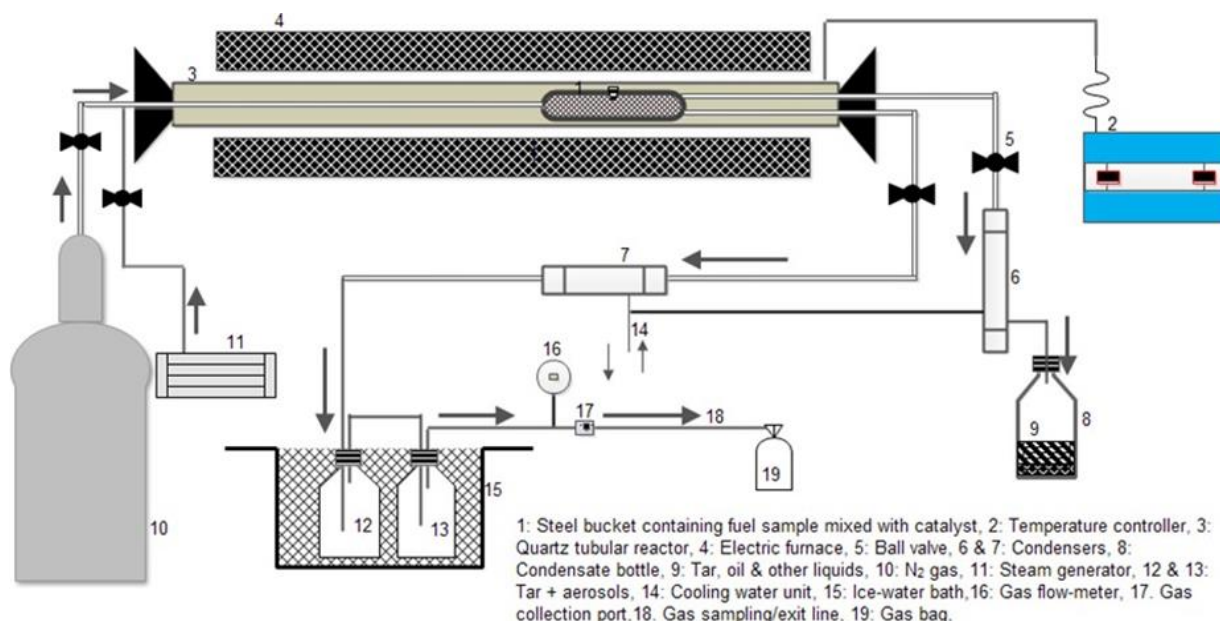


Figure 1: Bench-scale fixed bed gasifier

2.3. Experimental facility

The gasifier has an internal diameter and length of 45 mm and 550 mm respectively, and is made of stainless steel with high temperature resistance. Also fitted with the gasifier is an electric furnace and temperature regulator used for the heating and controlling of the temperature of the reactor; a steel-sheet bucket bed for feeding of feedstock; steam generator for steam supplies, flexible gasification fluid-

line; condenser fitted to a water cooling line; ice-water bath fitted to two condensate bottles for the collection of the gasification liquid product (tar & liquid aerosols); and product gas collection port where the gas is collected for gas chromatography (GC) analysis.

2.4. Gasification Experiment

The gasification test was carried out using Coal + PSD as feedstock under two operating process conditions namely; with catalyst

(WICAT) and without catalyst (WOCAT). Coal-to-PSD blend ratio of 1:1 was used, based on our previous research (Ozonoh et al., (2018) and Ozonoh et al., (2020). The gasification temperature conditions used were 700, 800, and 900 °C, respectively. From our previous report (Ozonoh et al., 2018), the ash content varied at different blend ratios. The study aimed to determine the effects of catalyst and gasification temperature on the gasification products (syngas and tar). The aforementioned effects were equally evaluated on gasification systems efficiencies (e.g. syngas yield, syngas composition, carbon conversion efficiency, cold gas efficiency, and Lower Heating Value (LHV) of gas.

In this study, a 20 g blend of Coal and Pine Sawdust (Coal + PSD) was loaded in a stainless-steel sheet basket as shown in Figure 1. The fuel was fed into the reactor following the temperature conditions mentioned earlier. Before feeding the fuel into the gasifier, the heated reactor was allowed for about 12 min to stabilize. Air and steam were used as gasification agents and were introduced into the system at flow rates of 200 ml.min⁻¹ and 0.2 g.min⁻¹, respectively. The volatile components of the fuel were released and they passed through the gas line via the condenser where tar and other liquids droplets (aerosols) and impurities (oil, water, and particulates) were condensed in a water bath containing blocks of ice. The condensates were collected using condensate bottles.

The flow rate of the exiting product gases was measured using a gas flow meter, while the produced gases were collected at the gas collection port located along the gas sampling/exit line using a gas syringe for compositional analysis using a GC.

Thereafter, the reactor was cleaned by flushing it with N₂ and air to prevent contamination in the next experiment. The test was repeated under the same experimental conditions, except that a mix of 2 g of PSD-BC and Ni-PSD-BC catalysts (10 % of Coal + PSD) was used – an operating process condition referred to in this study as with Catalyst (WICAT). The

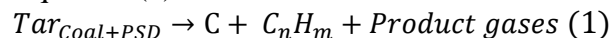
gasification test was also carried out Without Catalyst (WOCAT) at a residence time of 15 – 20 min from which the optimal time was determined as in WICAT. To ensure an effective catalyst activity, the steel basket containing a blend of the feedstock and catalyst was introduced into the reactor when the gasification temperature (900 °C) was stabilized. After the co-gasification process, the residual char contained in the basket was collected, measured, and packaged in a tight plastic container for analysis. The syngas yield, syngas composition, carbon conversion efficiency, LHV of the gas, and cold gas efficiency were estimated employing the results obtained from the results of gas analysis and feedstock characterizations.

2.5. Feedstock characterization

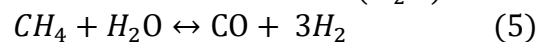
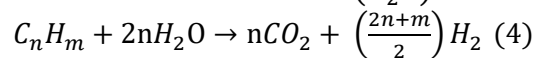
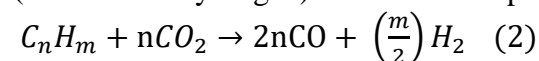
The results of feedstock characterization used for the co-gasification test include; proximate and ultimate analysis results as well as the calorific values. The lower heating value (LHV) was calculated from the Higher Heating Value (HHV) that was determined experimentally using an oxygen bomb calorimeter. The result of the characterization is shown in Table 1, but a detailed expression for the computation of the LHV of the gas and results of the characterization for Coal and PSD and other biomass samples (Coal + CC and Coal SCB) are contained in our previous papers (Ozonoh et al., (2018) and Ozonoh et al., (2020).

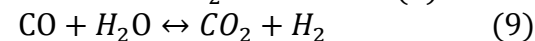
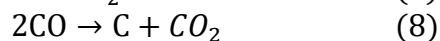
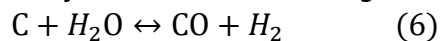
2.6. Basic Principles of Tar Cracking Process from Coal + PSD

The equation of reactions involving tar and other reacting species from the gasification process is expressed in Equation (1) to Equation (9):



The m and n in Equations (1) represent the number of moles of the reacting species (carbon and Hydrogen) in the reaction product.





The presence of water (H₂O) and carbon monoxide (CO) in the volatiles allowed for the regeneration of syngas (H₂ and CO) via Equation (2) through Equation (4) at high temperatures. In this case, the tar component (from Coal + PSD) was cracked into gaseous compounds via dry reforming over PSD-BC and Ni-PSD-BC-based catalysts, respectively. It is important to state that char reacted with the gases (e.g. H₂O or CO₂) during the process expressed in Equation (6) through Equation (7). The production of carbon and carbon dioxide as shown in Equation (8) via Equation (7) enabled the generation of more syngas (Taba et al., 2012) which in this study, is the desired product.

3. Results and Discussion

3.1. Feedstock Characterizations

The characterization results of the blend of Coal + PSD used in this study are presented in Table 1. It includes the Moisture Content (MC), Volatile Matter (VM), Fixed Carbon (VC), Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S), and Oxygen (O) contents of the feedstock.

From Table 1, it can be seen that the Matla coal used in this study has a very high ash content

of around 44.00 %, while the ash content of pine sawdust was as low as 0.59 % (Ozonoh et al., (2018) which is almost a zero-ash content. The results shown in Table 1 are within the range of results reported in the literature (Udomsirichakorn et al., (2014); Narvaez et al., (1996); and Luo et al., (2016).

Gasification of high ash-content coal poses a big threat to gasification efficiency because of the melting of ash at high temperatures during the gasification process. When ash is melted inside the gasifier due to high temperature or other factors, it could result in slag plugging the reactor tapping system (Ramarao and Vivekanandan, 2016). From Table 1, it can be seen that the ash content of the blend of Coal + PSD has reduced by around 97.35 % when compared to the ash content of coal. It is worthy to emphasize also that the majority of the South African coal samples are known for their high ash contents. This study therefore shall provide an opportunity of using the high ash content coal alongside low ash content fuel like PSD to produce syngas via co-gasification. Similarly, biomass has a highly volatile matter when compared to coal, and it contributes to high tar formation in biomass gasification (Ozonoh et al., 2020). Generally, the physio-chemical composition of the blend of Coal + PSD was enhanced in terms of the quality of the fuel, hence, ensuring better operational and gasification efficiencies.

Table 1: Results of the feedstock characterization for Coal + PSD

Proximate Analysis				Ultimate Analysis				
Feedstock: Coal + PSD								
Ash	MC	VM	FC	C	H	N	S	O
22.30	6.18	45.85	25.68	48.82	9.03	0.54	0.62	25.25
HHV of fuel [MJ/kg]				20.05				
LHV of fuel [MJ/kg]				18.88				

HHV: Higher heating value; LHV: Lower Heating Value; PSD: Pine Sawdust

3.2. Catalyst Characterization

3.2.1. X-ray diffractometer (XRD) and Transmission Electron Microscopy-Energy Dispersive X-ray Spectroscopy (TEM-EDS) Analysis

The XRD analyses of the biochar and Ni-biochar based catalysts were also carried out to determine their crystalline structure. The crystalline phase and TEM-EDS of the catalyst used in the gasification test are

displayed in Figure 2 and Figure 3, respectively.

The pattern shown by the biochar-based catalysts (PSD-BC) indicated that they possess strong amorphous structure within the range 6.9161 – 81.4099 (angular location) and with highest peak of 243.02 (in counts). This is quite different from the patterns

generated from the Ni-based catalysts (Ni-PSD-BC) and could be attributed to the amorphous nature of the catalyst support (biochar). For the Ni-biochar based catalysts, it can be seen that very sharp peaks were produced indicating the purity of the catalysts.

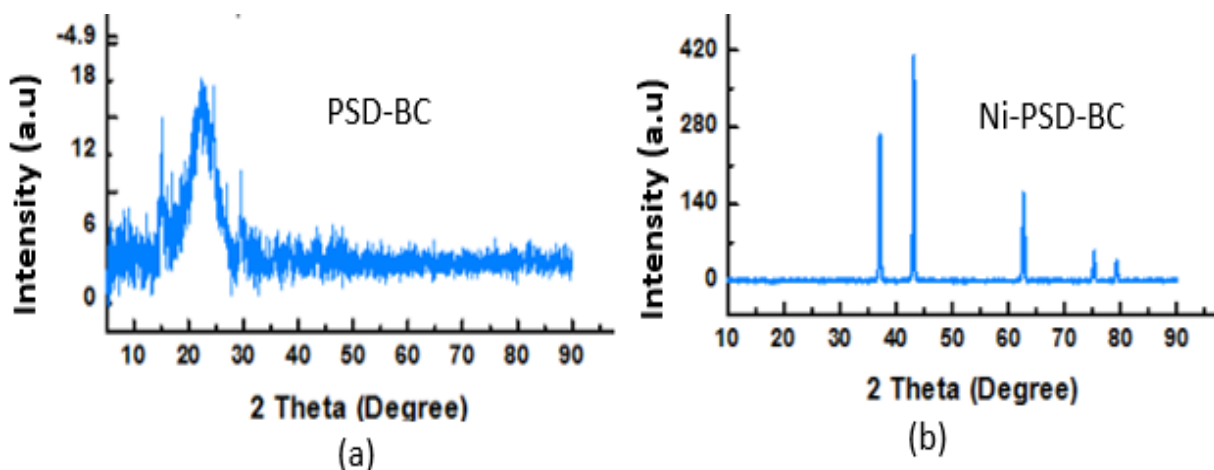


Figure 2: Crystalline phases of the catalyst: (a) PSD-BC (b) Ni- PSD-BC

From Figure 3 (TEM-EDX) of the catalysts, the spectrum of the biochar-based catalysts (a and b), indicates the amorphous nature of the catalyst based on the presence of the area peaks, which is not so prominent in the Ni-biochar-based catalysts.

The morphology of the Ni-biochar-based catalysts suggests a more solid

appearance/block which may be attributed to their crystalline nature when compared to the biochar-based catalysts. This is more prominent in the Ni-PSD-BC catalysts, which therefore affirms the result of the XRD reported for this catalyst as the optimum catalyst for tar cracking.

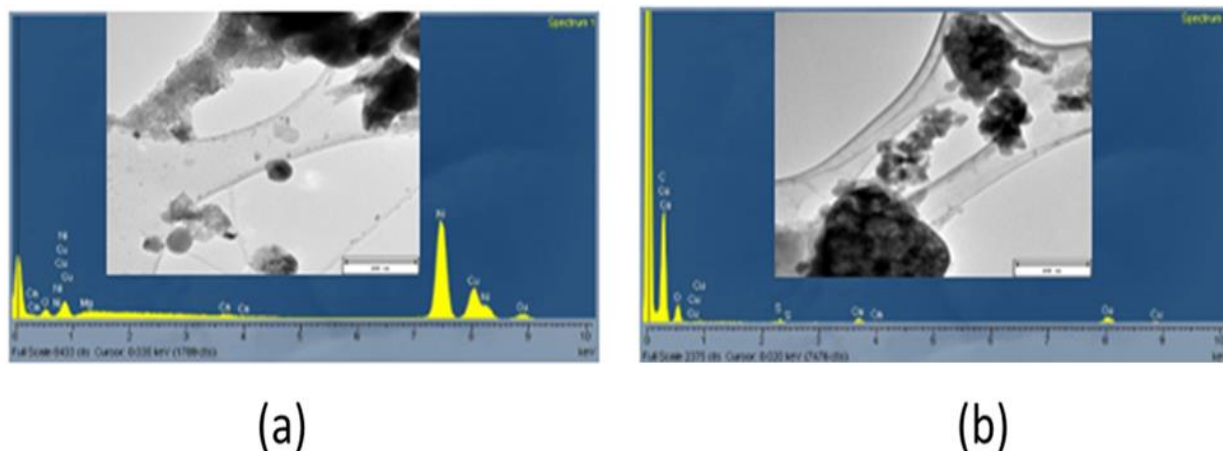


Figure 3: TEM-EDX of the catalysts (a) Pine Sawdust-Biochar catalyst (b) Nickel-Pine Sawdust-Biochar catalyst

3.2.2. Transmission Electron Microscopy

(TEM) analysis

The elemental composition of the catalysts is shown in Table 2. From Table 2, it can be observed that there is no presence of carbon in the Ni-PSD-BC & Ni-CC-BC. It may be attributed to the total combustion of carbon during the calcination process. On the other hand, it can equally be seen that the amount of carbon present in the biochar-based catalyst (PSD-BC) is considerably high. This could be because the biochar-based catalyst was not calcined, hence; affirming that the carbon

(amorphous) was completely burnt leaving only the crystalline phase of the catalyst. It can further be evident in the crystalline structures of the catalysts as displayed in Figure 3. However, the results of the elemental composition of the catalysts are in agreement with those found in the literature (Hervy et al., 2017); Brown et al., (2000); Yingxin et al., (2007); and Cheng et al., (2018).

Table 2: Elemental composition of the Ni-biochar & biochar-based catalysts

Element	Mass weight %	Molecular weight %	Atomic weight %	Mass weight %	Molecular Wt. %	Atomic weight %
	Ni-PSD-BC			PSD-BC		
C	-	-	-	85.38	42.29	90.05
O	5.53	25.00	17.53	10.96	33.83	8.69
Mg	40.82	17.86	0.84	-	-	-
Ca	1.09	14.29	1.13	2.41	11.49	0.76
Ni	92.97	42.86	80.26	-	-	-
S	-	-	-	1.26	11.49	0.50

Ni-PSD-BC: Nickel-Pine Sawdust-Biochar catalyst; PSD-BC: Pine Sawdust-Biochar catalyst; SCB-BC: Sugarcane bagasse- Biochar catalyst.

3.3. Estimation of gasification systems efficiency

Table 3 depicts the results of the gasification system efficiency. The gasification efficiency parameters studied are gas composition, carbon conversion efficiency, cold gas efficiency, gas yield, and LHV of gas. The expressions defining each of the indicators have been presented in our paper (Ozonoh et al., 2020). From Table 3, the cold gas efficiency increased with an increase in temperature from 50.35 – 55.95 % at 700 – 800 °C, but decreased to 46.66 % at 900 °C, while the carbon conversion efficiency (CCE) also increased with an increase in the temperature. Baskara et al., (2014), carried out a similar study and reported that the CCE increased from 60.25 – 67.88 % at 650 - 900°C, but in this study, there was a slight decrease of 5.80 % in the CCE from 800 - 900 °C when compared to what Baskara et al., (2014) reported. This may be attributed to differences in the catalyst activity or other operating process conditions employed during

the co-gasification process. For the CCE, the result was expected because a higher amount of carbon was decomposed at higher temperatures.

At times, temperature increases may not have a significant effect on the conversion of carbon. It happens when most of the carbon present in the fuels has been converted to gasification products (e.g. char & gases). For the LHV of the gas and in terms of catalyst performance, there was an increase in the heating value of the gas when Ni-PSD-BC catalyst as against the PSD-BC catalyst. This is an affirmation of the findings of Baskara et al., (2014). They reported that the LHV of gas increased from 5.90 – 6.01 MJ/m³ and decreased from 5.55 – 5.75 MJ/m³ using different types of catalysts and operating temperatures of 800 – 900 °C, respectively. It was a confirmation of the fact that the Ni-PSD-BC has higher catalytic activity than that of biochar-based (PSD-BC) catalyst.

Table 3: Results of performance of gasification system efficiency & amount of tar in the product gas using a bench scale FBG

Gasification efficiency parameters	Temperature condition [$^{\circ}\text{C}$]			Catalysts Temperature: 900°C	
	700	800	900	Ni-PSD-BC	PSD-BC
Carbon conversion efficiency [%]	57.90	68.59	70.78	53.93	50.11
Cold gas efficiency [%]	50.35	55.95	46.66	88.49	64.65
Gas Yield [kg/Nm^3]	1.71	1.95	2.27	2.85	2.51
LHV of gas [MJ/Nm^3]	5.50	5.36	3.80	5.80	4.81
Tar content [g/Nm^3]	12.96	8.25	8.01	4.55	4.96

Ni-PSD-BC: Nickel-Pine sawdust-biochar catalysts; PSD-BC: Pine sawdust-biochar catalysts; LHV: Lower Heating Value; FBG: Fixed Bed Gasifier.

3.4. Effect of catalyst on gas composition

The influence of the catalyst on the product gas composition was evaluated using Ni-PSD-BC and PSD-BC-based catalysts respectively. The syngas composition WICAT (Ni-PSD-BC and PSD-BC) was compared to WOCAT and is represented in Figure 4. It can be seen that the gas composition increased significantly on the application of catalysts than WOCAT for each of the product gas species studied. This is because catalyst activity enhanced the release of more volatile components of the fuel even at lower temperatures hence; resulting in its conversion into product gases.

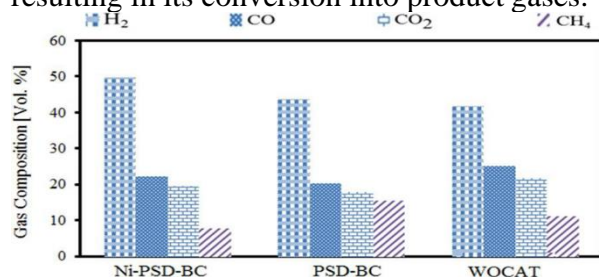


Figure 4: Influence of catalyst on product gas composition: At 900°C & steam as oxidant

3.5 Effect of temperature on gas composition

The effect of temperature on the product gas composition during co-gasification of Coal + PSD is presented in Figure 5. The composition of producer gas varied at different operating temperature conditions studied. From Figure 5, syngas (H_2 & CO) composition increased with an increase in the

gasification temperature, while the CO_2 and CH_4 contents were decreased. The increase in the H_2 content could be attributed to decomposition of the volatiles or cracking of the hydrocarbons (HCs) at increased temperature (Wang et al., 2011).

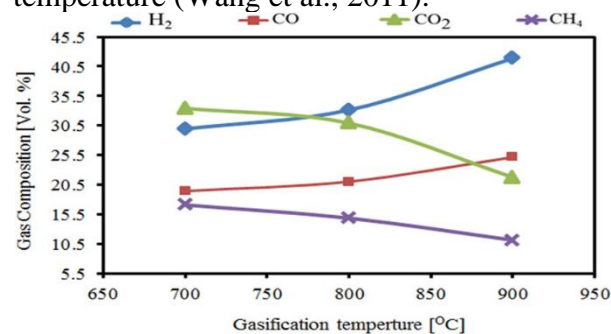


Figure 5: Influence of gasification temperature on product gas composition: At temperature range of $700 - 900^{\circ}\text{C}$, and air-steam as oxidant (WOCAT)

The H_2 and CO contents (syngas) increased from 29.95 – 41.87 % and 19.45 – 25.18 % when the temperature was increased from 700 – 900 $^{\circ}\text{C}$, respectively. This is also in affirmation with the result obtained by Baskara et al., (2014) [7] during the gasification of groundnut shells to produce gases. According to Baskara et al., (2014), there was an increase in the H_2 content from 10 – 20 % when the reaction temperature was increased from 730 – 830 $^{\circ}\text{C}$, while a decrease in the long chain hydrocarbons (HCs) from 3 – 5 % was observed for the aforementioned temperature condition. The reduction in the HCs enhanced the production of H_2 and CO during the process

(Baskara et al., (2014).

A similar finding was also reported by Yu et al., (2016). during co-gasification of pine sawdust and rice husk using CO₂-air as a gasifying agent. There was an increase in the syngas yield, but the content of CO₂ was higher than that of H₂, which could be attributed to the use of CO₂-air as against air-steam employed in this study which yielded hydrogen-enriched syngas. In this study, the syngas produced at 900 °C was higher than that of 700 °C by 16.65 % and lower than that produced by WICAT (at 900 °C) by about 8.61 %. The composition of syngas in the produced gas WICAT was equally higher than that of WOCAT (at 900 °C) by 5.82 %. This is also related to the increase in conversion of volatiles and tarry compounds at increased temperature and catalyst activity on the reacting species.

3.6. Effect of gasification temperature on gas yield

Figure 6 and Figure 7 shows how the gas yield is affected by temperature during the co-gasification of coal and biomass. Figure 6 explains only the temperature effect on the gas yield, while Figure 7 describes the effect of temperature and catalysts on gas yield. The technical demonstration of the effect of catalyst and gasification temperature on the gas yield is shown in Figure 7. From Figure 7, the gas yield increased from 1.71 - 2.27 kg/Nm³ when the temperature was increased from 700 – 900 °C. There was a significant increase in the gas yield from the minimum temperature (700 °C) to the maximum (900 °C) gasification temperature by around 14.07 %; thus, indicating that an increase in temperature favored the product gas yield.

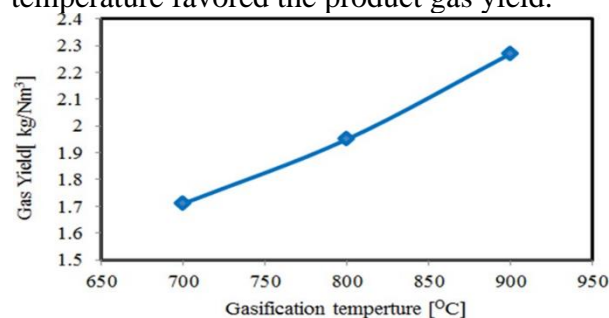


Figure 6: Influence of gasification temperature on product gas yield

The relationship between gasification temperature and gas yield with catalyst (WICAT) and without catalyst (WOCAT) for the co-gasification reaction is displayed in Figure 7.

From Figure 7, X is the gas yield from thermal cracking (WOCAT_T); ΔX is the change in gas yield due to the use of catalysts during the co-gasification test; X₁ is the gas yield at 700 °C; X₂ is the gas yield from co-gasification without catalyst (WOCAT) and X₃ is the gas yield from co-gasification with catalyst (WICAT). The ΔX was calculated from the difference in gas yield between the co-gasification test WOCAT (X₂) and the co-gasification test with WICAT (X₃) at 900 °C, respectively. The value of ΔX obtained when Ni-PSD-BC and PSD-BC catalysts were used for the co-gasification reaction were 11.33 % and 5.02 % higher than that of co-gasification process WOCAT.

Secondly, the product gas yield for X₁ is higher than that of X₂ by around 14.07 %, but X is lower than that of ΔX (WICAT) by 11.33 % at a gasification temperature of 900 °C. Similar results had been reported by Shen et al., (2015) and Zhang et al., (2015), respectively. The implication as can equally be seen in Table 3 is that gas yield increased with an increase in temperature, but increased further when the Ni-PSD-BC and PSD-BC-based catalysts were employed in the co-gasification process. It could also be attributed to the conversion of more chars, volatile materials, and cracking of tars by the gasifying medium and catalysts (Baskara et al., (2014) and Guo et al., (2018).

As explained earlier, the increase in the gasification temperature increased the gas yield on the basis that more tars were converted into small molecular HCs and gases, while higher gas yields were observed when catalysts were employed. The increase in the product gas yield could be attributed to the thermo-chemical reactions occurring amongst the reacting species (e.g. gas, char, and catalyst). The reaction condition can be well understood as described in Equation (1)

through Equation (9) of section 2.6.

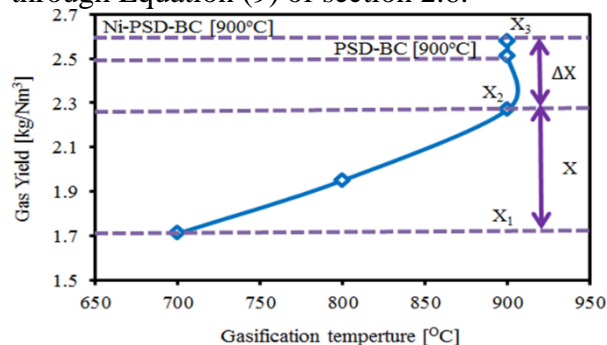


Figure 7: Effect of gasification temperature on product gas yield

3.7. Tar in the product gases

The amount of tar present in the product gases obtained from co-gasification of Coal + PSD at 700, 800 and 900 °C, WICAT and WOCAT were studied as displayed in Table 4. Temperature was found to have a very significant influence in the cracking of tar. It was demonstrated on the concentration or amount of tar contained in the product gas. The amount of tar present in the gas decreased with an increase in the temperatures studied. A considerable decrease in the amount of tar in the gas was observed when the co-gasification was carried out WICAT. From Table 4, it can be seen that the amount of tar when Ni-PSD-BC catalyst was used at 900 °C was lower than that of the WOCAT under the same temperature condition, thus; implying that the catalyst has a strong effect on tar reduction. It is worth noting that the amount of tar in the

product gas when Ni-PSD-BC was employed in the co-gasification experiment was lower than that of the PSD-BC catalyst by around 4.31%. Furthermore, the tar content in the product gas WOCAT at 900 °C was higher than that of WICAT at the same temperature (900 °C) by around 27.55%. The use of catalysts has significantly enhanced the reduction of tar in the produced gases.

Importantly, from the aforementioned results, the quality of gases generated at 700, 800, and 900 °C WOCAT respectively, do not meet the standard recommended for applications in fuel cells and gas turbines (in terms of tar contents) for electricity production. The allowable tar limit for different energy conversion devices can be found in the literature review section of this thesis (Lu et al., (2012); Guo et al., (2007); and Iversen et al., (2006). Similarly, the gases produced by WICAT at 900 °C can be used in internal combustion engines and gas turbines, but unfortunately, have a low quality to be used in fuel cells for electric power generation. For the produced gas to be considered of high quality for use in fuel cells it must undergo cleaning in a secondary reactor, however, gas cleaning is not a cost-effective process. In this case, modification of the current gasifier or use of a fluidized bed gasifier (BFB & CFB) or other conversion technologies, as well as improvement of experimental process conditions is required to upgrade the quality of the gas.

Table 4: Compositional tar analysis result of Coal + PSD tar (CPSD-T)

Peak number	Hold time	Compound name	Relative percentage*	% of tar in Coal + CC
1	3.453	Cyclopentanone	0.33	1.14
2	3.812	Propane, 2,2'-[ethylidenebis(oxy)] bis-	1.09	0.52
3	3.923	1,6-Heptadien-4-ol	1.09	0.66
4	4.001	2-FURANCARBOXALDEHYDE	8.89	0.87
5	4.430	PROPANE, 1-(METHYLETHOXY)-	2.08	0.61
6	4.505	2-Butanon	2.09	0.95
7	4.613	2-Furanmethanol	5.26	1.26
8	4.765	2-Propanone, 1-(acetyloxy)-	4.32	0.92
9	5.045	2(3H)-Furanone, dihydro-4,5-dimethyl-	0.52	1.13
10	5.345	Chloroacetic acid 3-methylbutyl ester	0.5	1.11

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11	5.520	2-(4-METHYLPHENOXY) N-(1,3-THIA	1.56	1.17
12	5.578	2-Cyclopenten-1-one, 2-methyl-	2.51	1.04
13	5.709	Ethanone,1-(2-furanyl)-	0.94	0.83
14	5.788	2(3H)-Furanone, dihydro-	1.59	0.86
15	5.863	ALPHA., BETA-CROTONOLACTONE	2.04	1.13
16	5.980	4,5-Trimethylene-2H-1,3-oxazine-3H-2,6-	0.62	0.89
17	6.126	Ethanol, 2,2-diethoxy	6.19	0.83
18	6.397	2(3H)-Furanone, 5-methyl-	0.73	1.12
19	6.553	Butanedioic acid methylene-	0.52	1.00
20	6.626	Propyl nitrite	0.54	0.64
21	6.796	2-Propanamine, N-ethyl-	0.71	1.48
22	6.915	2-Butanone, 1-(acetyloxy)-	1.27	0.68
23	6.967	Octane, 1-axido-	2.46	1.17
24	7.147	Ethanol 2,2-diethoxy-	0.32	0.63
25	7.300	2(5H)-Furanone, 3-methyl-	0.41	0.67
26	7.505	3-Ethyl-5-methyl-4-[3-(thiophen-3-yl) (1,]-	1.02	1.17
27	7.575	Cyclohex-3-enecarboxaldehyde, 2,4,6-trin	0.66	4.40
28	7.620	4-	1.27	4.10
		(METHYLSULPHONYL)TETRAHYDRO		
29	7.690	2-Decanynoic acid	1.01	2.59
30	7.798	Phenol	5.1	1.28
31	7.886	1,6-Heptadien-4-ol	1.69	0.73
32	8.065	2,3,4,5-TETRAMETHYL-2-CYCLOPEN	22.51	1.50
33	8.310	2-DEOXY-N-(4-METHYL-3-	0.76	0.75
		NITROPHENE		
34	8.355	1,2,4-THIADIAZOL-5-AMINE, 3-ALLYI	0.37	0.64
35	8.472	3-Methylcyclopentane-1,2-dione	3.51	0.96
36	8.545	7H- [1,3] Thiazolo[3,2-a] pyrimidin-7-one	0.59	0.58
37	8.615	5-Hydroxy-2-heptanone	0.46	0.69
38	9.038	Furan, 2,5-diethoxytetrahydro-	0.46	0.58
39	9.104	Ethanone, 1-cyclohexyl-	0.39	0.61
40	9.300	phenol, 2-methyl-	1.37	1.15
41	9.363	Decane-5,6-d2	0.76	0.76
42	9.434	2,4-Dimethyl-1,3-dioxolane (mixed isomers)	0.35	0.45
43	9.583	4-Aminobutyraldehyde diethyl acetal	0.47	0.55
44	9.686	N HEPTANAL	1.62	1.45
45	9.794	phenol, 2-methoxy-	5.68	1.03

4. Conclusions

An evaluation of the effects of locally synthesized catalysts and gasification temperature on gasification products and gasification systems efficiency was carried out in a bench-scale fixed bed gasifier. Coal-to-PSD blend ratio of 1:1 was used. Two operating process conditions namely; with catalyst (WICAT) and without catalyst (WOCAT), at 700, 800, and 900 °C temperatures and

residence time of 15 – 20 min were considered, respectively. The choice for the particle size of the feedstocks used in this study was based on our previous findings (Ozonoh et al., (2018) and Ozonoh et al., (2020). Nickel-pine sawdust-biochar (Ni-PSD-BC) and pine sawdust-biochar (PSD-BC) were used as catalysts. The gases and tars produced from the aforementioned process conditions were

analyzed in a GC and the following conclusions were made:

- Co-gasification of Coal + PSD is instrumental to using high ash content South African coal such as Matla coal for the production of syngas for electricity generation.
- The co-gasification performance efficiency of the gasifier was significantly enhanced when the co-gasification process was carried out WICAT as against WOCAT.
- The syngas yield when Ni-PSD-BC and PSD-BC (WICAT) were used was higher than that of WOCAT by 11.33 % and 5.82 %, respectively, but the product gas yield at 900 °C was higher than that of 700 °C (thermal cracking) by 14.07 %. The implication is that increase in temperature and use of catalyst favoured gas production.
- H₂ and CO (syngas) contents increased from 29.95 – 41.87 % and 19.45 – 25.18 % at 700 – 900 °C, respectively. The syngas composition was significantly enhanced during co-gasification WICAT. The implication is that production of hydrogen-enriched syngas was enhanced by using catalyst due to tar cracking and reactivity amongst species (e.g. char, gases, and catalyst).
- The content of tar in the product gas is in the range of 8.01 – 12.96 g/Nm³ for 700 – 900 °C temperature condition and 4.55 – 4.96 g/Nm³ when PSD-BC and Ni-PSD-BC catalysts were used, respectively. It implies that catalytic cracking is more effective than thermal cracking in terms of tar reduction.
- The quality of gases produced at 700, 800 and 900 °C WOCAT were not suitable for use in fuel cells and gas turbines, while the Syngas produced at 900 °C WICAT, can be used in internal combustion engines and gas turbines, but unfortunately, of lower quality to be employed in fuel cells for electricity

production.

- The optimal operating time for the two operating process conditions namely; With Catalyst (WICAT) and Without Catalyst (WOCAT) were 12 min and 17 min, respectively.

In this study, only one biomass (PSD) sample was used in the gasification test and it was based on the findings from our previous researches (Ozonoh et al., (2018) and Ozonoh et al., (2020)). It will be necessary to study other agro-based biomass samples such as corn cob and sugarcane bagasse to validate our previous report which inferred that; pine sawdust (PSD) was the most viable feedstock in terms of co-gasification of high ash content South African coal and biomass. However, results from this study will be used by stakeholders for decision making and as well, open window for further research in this area.

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