A review on the effect of feed oxygen, water concentration, temperature and pressure on gasification proces

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Abstract—Much interest is currently being shown on Gasification technology due to its versatility, the various technological arrangements it exhibits and its environmental advantage in converting any biomass or coal into a clean syngas. Many people have conducted studies on gasification processes in the past, but these results are mostly scattered, making it hard to keep track of the findings. This paper presents a comprehensive review of the literature on the effect of various gasification process parameters like feed oxygen, steam concentrations, pressure and temperature on syngas composition, heating value and the efficiency of gasifiers. The review seeks to streamline the information with the objective of determining the optimal gasification process conditions for best quality and quantity of syngas. Reviews of gasification technologies and process classifications are also presented.

Keywords—Gasification, Oxidizing agent, Feedstock, Syngas.

I. INTRODUCTION

THE energy demands today is quite high and meeting these needs is one of the most important challenge of modern world. Despite constant development of new technologies and increase of usage of renewable energy sources, the conventional fossil fuel plays crucial role as an energy sources. One of these fossil fuels is coal. Coal has been used for many decades for production of energy with many developed countries deriving the bulk of their electrical energy from it. But due to strict environmental requirements especially concerning the levels of unwanted emissions permitted, better methods of utilizing coal as an energy source has been necessitated [1]. One such method is gasification process in which the solid fuel is converted to desirable gaseous fuel and the methods of separation and utilization of the environmentally harmful emissions like carbon dioxide, oxides of Sulfur and oxides of Nitrogen can be incorporated. Though gasification is an old technology, the variety of the technological arrangements like fixed-bed, fluidized-bed and entrained-flow reactors and its versatility (production of electricity, syngas, hydrogen) render it a current topic of research.

The traditional technologies for utilizing coal for power generation included grated coal firing plants where the fuel was mechanically distributed onto a moving grate, at the bottom of the firebox, in a partially crushed gravel-like form. Later pulverized coal power plants were introduced where coal was ground into powder. These were broken down into three categories; sub-critical pulverized coal plants which operated below the critical point of water (647.096 K and 22.064 MPa). super-critical pulverized coal plants, and ultra-super-critical pulverized coal plants which operated above the critical point of water. These methods, however, were environmentally unfriendly due to unwanted emissions which included oxides of sulfur, oxides of nitrogen, carbon dioxide and particulates. They also had low plant efficiencies which were at about $\leq 35\%$ for sub-critical plants , about 35-40% for super-critical plants and in the range of 40-45% for ultra-super-critical plants [2]–[4]. In all these, power production involved using coal to heat water and produce steam.

Gasification is a thermo-chemical process taking place at high temperatures typically above 700^oC to convert carbonaceous materials including biomass, fossil fuels, plastics, and coal into syngas; which is a mixture of H_2, CH_4, CO, and CO_2. Limited amount of oxygen and/or steam is used as the gasifying agent and heat carrier agent.

In the recent years, Integrated coal Gasification Combined Cycle (IGCC) has been used as an alternative to the coal fired plants in which oxidizing agents like steam, oxygen, air, or their combinations are used to change coal into syngas which is then used as fuel for power production giving improved plant efficiencies. In these plants coal reacts with the oxidizing agents to produce a CO, H_2 and CH_4 rich gas which is then taken to gas turbines to produce power and the flue gas taken through steam turbines to produce power. These systems are coupled with CO_2 capture and gas purification systems which eliminates harmful emissions to the environment making them environmentally friendly.

II. GASIFICATION PROCESS OVERVIEW

A. Stages in a Gasification Process

Coal gasification processes are undertaken in the presence of oxygen, steam, air, carbon dioxide or their combinations in different proportions. A syngas with different composition (with combustible and non-combustible components) and heating value is obtained. The non-combustibles components are removed, using different methods, to produce a clean syngas that can be used as a fuel to generate electricity or steam, as a

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basic chemical building block for a large number of uses in the petrochemical and refining industries, and for the production of hydrogen. Thus gasification adds value to coal by converting it to marketable fuels and products [5], [6].

The quality and efficiency of the gasification process, equipment and the products depend on the quality of the feedstock used, the composition, flow rate and the temperature of the oxidizing medium, and the prevailing temperature and pressure in the gasifier [7]. It is also important to consider the way of injection of the oxidizing agent like in a two-stage gasification process, the reactor may be supplied with air in the first stage and with steam in the next stage, or the oxygen may be injected in the two stages or a mixture of the oxygen and steam [8], [9]. All these factors need to be understood for an optimum output from the gasification process.

Generally, the gasification process can be divided into the following stages [10]–[13], [29], which occur consecutively:

1) Drying: In this stage, the moisture content of the biomass is reduced. Typically, the moisture content of most biomass vary from 5% to 40%. Drying process take place at between $100^oC - 200^oC$ with a reduction in the moisture content of the biomass to below 2%.

2) Devolatilization (Pyrolysis): This is a stage of thermal decomposition of the biomass in the absence of oxygen or air. In this stage, the volatile matter in the biomass is reduced leading to the release of hydrocarbon gases from the biomass. This process reduces the biomass to solid charcoal or char. These hydrocarbon gases can condense at a sufficiently low temperature to generate liquid tars. Factors influencing the devolatization process vary at different stages of the gasification process and depend on the reactor space. These factors include: temperature, pressure, heating rate, reaction atmosphere, particle size and the degree of comminution of coal [10].

3) Oxidation: This is a stage of reaction between char and oxygen in the presence of air or oxygen, resulting in formation of CO_2. The hydrogen available in the biomass is also oxidized to generate water. A large amount of heat is released with the oxidation of carbon and hydrogen. If the oxygen available is in sub-stoichiometric quantities, then partial oxidation of carbon may occur, resulting in the generation of carbon monoxide hence gasification stage.

4) Reduction: This process takes place in the absence or sub-stoichiometric presence of oxygen. At this condition several reduction reactions occur in the $800^oC - 1000^oC$ temperature range. and these reactions are mostly endothermic. The main reactions in this category are the water-gas shift, Boudouard, and methanation.

B. The Chemistry of Gasification

When coal is injected into a high-temperature gasifier, a series of physical and chemical processes occur in the gasifier. The particles are quickly heated, the moisture is evaporated, the volatile matter in the coal is devolatilized and the char is burned or gasified. The gaseous products released from the coal particles will also react with each other according to the surrounding environmental conditions and their intrinsic kinetics mechanism. These reactions in the gasifier are either exothermic or endothermic [15].

Rajul Nayak *et al* [16], in their simulation of gasification process, stated that the heat released by the exothermic reactions of coal and oxygen maintains the reactor at the operating temperature and supports the endothermic gasification reactions occurring inside the gasifier. They further explained that steam can only be used as a sole gasifying agent if an external source of heat that drags the endothermic reactions forward is provided.

One of the main processes is combustion of coal, which is an heterogeneous exothermic reaction between carbon from coal and oxygen to produce carbon dioxide and carbon monoxide as seen in (1) and (2) below [17]. Equation (2) is called Boudouard reaction.

$$C + O_2 \rightarrow CO_2 \quad (-393 MJ/kmol) \tag{1}$$

$$C + \frac{1}{2}O_2 \rightarrow CO \quad (-111 MJ/kmol) \tag{2}$$

The char-steam in (3) and char-CO_2 in (4) gasification reactions are endothermic and rely on the heat from the exothermic combustion reactions.

$$C + H_2O \rightarrow CO + H_2 \quad (+131 MJ/kmol) \tag{3}$$

$$C + CO_2 \rightarrow 2CO \quad (+172 MJ/kmol) \tag{4}$$

There is an heterogeneous reaction of carbon with hydrogen as shown in (5) which is exothermic and produces methane.

$$C + 2H_2 \rightarrow CH_4 \quad (-75 MJ/kmol) \tag{5}$$

Apart from the heterogeneous reactions above, homogeneous reactions among the gases also occur in the reactor as seen below in (6), (7), (8), (9) and (10). Equations (9) and (10) are called methanation reactions

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (-283 MJ/kmol) \tag{6}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (-242 MJ/kmol) \tag{7}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (-41 MJ/kmol) \tag{8}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (-206 MJ/kmol) \tag{9}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (-165 MJ/kmol) \tag{10}$$

In general, for a constant coal feeding rate, when the O_2/coal ratio is increased and then the reaction temperature is high, then the reaction 4 becomes active and consumes the CO_2 generated from reaction 1 causing the concentration of CO_2 in the product gas to fall. However, high O_2/coal ratio leads to increased concentration of CO_2 due to excess supply of O_2 and the coal is mostly under combustion in the reactor.

C. Gasification Process Classifications and Technologies

Gasification process can be categorized in several ways [18]: (a) by the gasifying agent, such as air-blown, oxygen blown, or steam gasifiers; (b) by the source of heat, either as auto-thermal (direct) where heat is supplied by partial combustion of biomass, or allothermal (indirect) gasifiers where heat is supplied by an external source through a heat exchanger or an indirect process like solar or plasma gasification; (c) by the gasifier pressure, as atmospheric or pressurized. (d) by the reactor design and that follows three main subcategories: high temperature entrained flow, fixed bed (sometimes referred to as moving bed), and fluidized bed gasifiers. The most common classification method is the fourth one and thus a brief description of each gasifier type is presented below

1) Fixed (or Moving) Bed Gasifiers: Moving bed gasifiers are counter-current flow reactors in which the particle enters at the top of the reactor and air or oxygen enters at the bottom. As the particle slowly moves down through the reactor, it is gasified and the remaining ash drops out of the bottom of the reactor. Because of the counter-current flow arrangement, the heat of reaction from the gasification reactions serves to pre-heat the particle before it enters the gasification reaction zone. Consequently, the temperature of the syngas exiting the gasifier is significantly lower than the temperature needed for complete conversion of the particle. Fixed bed gasifiers are simple to construct and generally operate with high carbon conversion, long feedstock residence time, low gas velocity, and low ash carry-over [19], [20].

2) Fluidized Bed Gasifiers: A fluidized bed gasifier is a back-mixed or well-stirred reactor in which there is a consistent mixture of new particle particles mixed in with older, partially gasified and fully gasified particles. The mixing also fosters uniform temperatures throughout the bed. The flow of gas into the reactor (oxidant, steam, recycled syngas) must be sufficient to float the particles within the bed but not so high as to entrain them out of the bed. However, as the particles are gasified, they will become smaller and lighter and will be entrained out of the reactor. It is important that the temperatures within the bed are less than the initial ash fusion temperature of the particle to avoid particle agglomeration. These gasifiers are characterized by short residence time, high temperatures, high pressures, and large capacities [21]

3) Entrained Flow Gasifiers: A finely ground particle is injected in concurrent flow with the oxidant. The particle rapidly heats up and reacts with the oxidant. The residence time of an entrained flow gasifier is seconds to several seconds. Because of the short residence time, entrained flow gasifiers must operate at high temperatures to achieve high carbon conversion. Consequently, most entrained flow gasifiers use oxygen rather than air and operate above the slagging temperature of the particle.

III. The Influence of Process Conditions on Gasification

A. The Effect of Oxidizing Agent on the Gasification Products

Lee H. *et al* [22] developed a model to analyze chemical reaction processes in a dry-feeding entrained-bed coal gasifier as a function of O_2/coal mass ratio, steam/coal mass ratio, and operating pressure. In their study, initially O_2/coal ratio was varied from 0.3 to 0.9 with a constant steam/coal ratio of 0.05. Later, steam/coal ratio was varied from 0.01 to 0.2 with an O_2/coal ratio of 0.75, the pressure inside the reactor being kept at a constant value of 4.2MPa, They observed that increasing O_2 concentration increased carbon conversion rate leading to enhanced syngas yield while decreasing O_2 concentration lowered carbon conversion rate. Also increasing H_2O concentration slowly increased carbon conversion efficiency during the initial reaction stages but the rate improved with time. This was because increasing steam concentrations led to decrease in the overall temperature in the reactor and cold gas efficiency. They however did not show the effect of these parameters on gasifier temperature.

Park T. J. *et al* [23] studied the characteristics of entrained-flow coal gasifier. In their research they stated that, the O_2/coal ratio is critical to the carbon conversion for a short residence time reactor, since the endothermic gasification reactions are supported by the heat produced from exothermic reactions. They concluded that for such a gasifier O_2/coal ratio of between 0.8 and 0.9 is required. this would give better carbon conversion and increased cold gas efficiency. Their study however only involved a slurry-fed entrained-bed gasifier. and thus further study is necessary for a dry-fed gasifier.

Alina Zogala [24] did a thermodynamic equilibrium simulation to determine factors affecting syngas composition from coal gasification. He used coal from four different Polish coal mines: Belchatow (lignite), Bielszowice (sub-bituminous) and Ziemowit and Bobrek (both bituminous). He used three forms of gasifying agents: mixtures of steam-pure oxygen, steam-air and air-pure oxygen. He found out that raising the concentration of O_2 in the gasifying agent led to significant rise in molar yield of CO, H_2. Carbon dioxide and H_2O yield also grew, though the yield of CO_2 exceeded that of H_2O at higher O_2 concentrations. Similar trends were seen when using steam in the gasifying agent. Much yield in H_2 was realized when H_2O concentrations were increased that when only O_2 and air were used. This is shown in his graph presented in Figures 1 and 2. His operating temperatures were however low (700^{o}C) compared to those experienced in fixed bed gasifiers. He also assumed that the process was isothermal in the reactor which is not the case in the actual practice.

Babu B. V. *et al* [25] modeled a biomass gasifier to show the effects of O_2/air and steam /air ratio on gasification process. Their results were in agreement with those of Alina Zogala [24]. But they went further and found out that the calorific value of the syngas increased with increasing O_2/air ratio but decreased with increasing steam /air ratio and that the reaction temperature also increased for preheated air intake. Their model was however based on wood as the feedstock which is high in volatile matter compared to coal.

Jorge E. Preciado *et al* [26] also did a simulation on gasification of Colombian Coal in a fluidized bed gasifier and got a similar results. In their study they attained a maximum thermal efficiency of 62.6%, that corresponded to a slurry solid concentration of 0.65, a O_2/carbon ratio of 0.64, steam to dry gas ratio of 0.59, and low temperature reactor operating

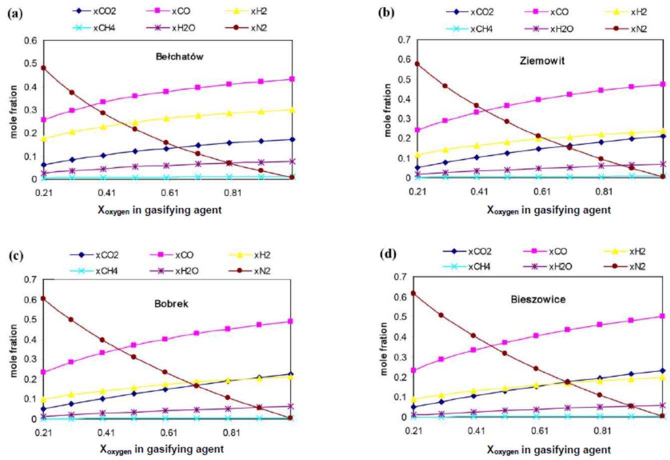

Fig. 1. The effect of oxygen/air ratio on syngas composition (at 700^{o}C) [24]

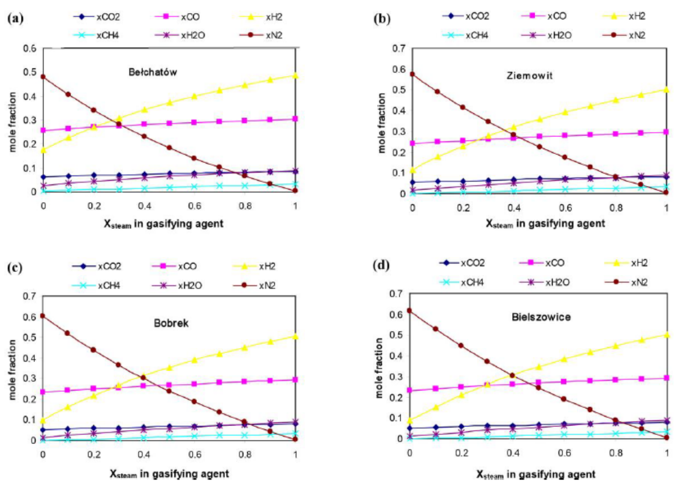

Fig. 2. Effect of steam/air ratio on syngas composition (at 700^{o}C) [24]

temperature of 473 K. They found that thermal efficiency of the process is most sensitive to O_2/ carbon ratio and that an excessive increase in the O_2 flow rate causes a fall in thermal efficiency. They then concluded that the O_2/carbon ratio should not exceed 0.8 for efficient operations. The simulation was however based on low temperature reactor (LTR). These findings are in agreement with those realized by Hao Xie *et al* [27] who simulated coal gasification based on slurry-fed entrained-bed gasifier.

Haibin Li *et al* [28] studied the effect of oxygen flow rate on gasification products and found out that the amount of CO rose gradually as the O_2 flow rate approached 20 kg/h beyond which the molar fraction of CO decreased. The amount of H_2 decreased gradually as the mass flow rate of O_2 rose. They concluded that the optimum LHV of the syngas would be obtained when the O_2 flow rate was 20 kg/h and that preheating of the O_2could both improve the syngas heating value and the reaction temperature. Their study was however based on pure oxygen and pure carbon dioxide as the gasifying agents which yields a syngas with fairly low heating value due to low hydrogen content. These results also agree with conclusions by Rukayya Ibrahim Muazu *et al* [29] who modeled a fluidized bed gasifier for agricultural biomass gasification based on air as the oxidizing agent. Their air flow rate was 4.5 kg.h

B. The Influence of Gasifying Medium on the Reactor Temperature and Pressure

Biagini E. *et al* [30] modeled a gasifiers for hydrogen production optimization. They varied the O_2/coal ratio and the H_2O/coal ratio from 0.25-0.50, and 0.0-0.35 respectively. They found out that the higher the O_2/coal ratio, the higher the reactor temperature. They did not however identify the optimum values for the oxygen/coal and steam/coal ratios that could give most favorable operating temperature for the efficient production of quality syngas. increasing air flow rate also leads to increased temperature in the reactor as well as temperature of the syngas at outlet [13]

Park T. J. *et al* [23] in their study realized that temperature distribution inside reactor depended upon the feed rate of coal and oxygen unless heat losses were considered. They showed that reactor temperature rose with increase in O_2/coal ratio. They concluded that, considering the ash melting temperature and heat losses from the reactor, the desired O_2/coal ratio were at least 0.6. They also found out that the O_2/coal ratio affects carbon conversion more significantly than the steam/coal ratio. They however did not explore how the heat losses could be minimized to increase the efficiency of the process.

Weihong Yang *et al* [31] analyzed the influence of a preheated feed air on the performance of a fixed-bed biomass gasifier. They found out that when higher air temperature are used, the temperatures of the solid fuels rise from room to peak temperature more quickly compared to when lower air temperature is used, indicating that a fast ignition occurs. They observed from their model that, a feed air of temperature equal to 973 K, the solid peak temperature at the bed top was only 630 K while it was about 900 K for the case of feed air temperature equal to 623 K. This implied that the peak temperatures are lower when higher feed air temperatures are used. This was because the ignition temperature is much lower when high feed gas temperatures are used. Preheating the feed air to this high temperatures is adds to the cost of the gasification system due to specialized materials needed to contain such high temperatures.

H. Lee *et al* [22] in their model explained that the increase in steam/coal ratio lowers the temperature due to the relatively high heat capacity of steam. As a result, the generated syngas concentration is low save for hydrogen due to the high steam concentration. They also noted that increasing the operating pressure improved both carbon conversion and cold gas efficiency because the reactivity of char + H_2O and char + CO_2 increased. They observed that during the early stages of combustion and gasification reactions the rate of increase of temperature was higher as pressure increased, but overally the peak temperature was low. This was attributed to the reactivity of endothermic gasification reactions that become active fast after oxygen is consumed because of the combustion of volatiles. They then concluded that the gasifier operating pressure is inversely proportional to the peak temperature. This model was however not validated due to lack of literature with data on dry-fed gasifiers that could be used to bench mark the same.

C. *The Effect of Temperature and Pressure on the Gasification Process and Products*

Nearly all the coal gasification reactions are normally reversible and thus the equilibrium point of any of these reactions can be shifted by manipulating the temperature. This therefore illustrates that temperature, as a parameter, has a great influence on the performance of coal gasifiers. The degree of the equilibrium attained by the various coal gasification reactions in the gasifier reactor determine the composition of the volatile matter generated from the gasifier. [32]

Jianxin Mi *et al* [33] compared the char yields, surface area and pore volumes of different coals as a function of gasification temperature in the fluidized-bed reactor at the slow heating rate. They observed that the three parameters above generally decreased with increasing reaction temperature from 700 to 900^{o}C in 15 vol % steam. Yaning Zhang *et al* [34] found out that increase in reactor temperature had a positive impact on syngas energy and exergy. These results were however based on fluidized bed gasifiers, with steam as the gasifying agent. There is thus need for further studies using dry-fed gasifier with inclusion of other gasifying agents like oxygen, air or their mixtures.

Idowu Adeyemi *et al* [35], Leila Emami *et al* [36] in their studies showed that increase in reactor temperature and pressure led to the formation of more CO, H_2 and higher calorific value due to improved endothermic reactions between char and steam and carbon dioxide. The heat in this study was however supplied from built-in heating modules which is different from the practical processes where the heat is majorly from the exothermic reaction in the reactor. These conclusions were also in agreement with the study conducted by Shermina Begum *et al* [37] who modeled an integrated fixed-bed gasifier operating on different biomass feed stocks. They further concluded that an average temperature of 700^oC provided an ideal condition for their modeled gasifier.

Marek Balas *et al* [38] conducted experiments to investigate the effects of temperature and pressure on the gasification process. After their study they found out that increase in temperature leads to increase CO and H_2 yield, an increase in syngas lower calorific value but decline in the yield of CH_4 and CO_2. They also found out that change in pressure however has a contrary effect.

Neville A. H. Holt [39], in his study of needs and opportunities in coal gasification field, noted that the commercial gasifiers from Global E-Gas and Shell generally operate at higher temperatures and that this accounted for the better carbon conversion rates experienced in these gasifiers with petroleum coke. He observed that increasing the operating temperature would however certainly aggravate the refractory wear, a replacement of which is very expensive and time consuming. This shows the need to control the operating temperatures of the gasifier.

Wadhwani *et al* [40] conducted a 2D CFD simulation to investigate the effects of operating pressure for coal chemical looping combustion. The results obtained showed that the operating pressure had a reverse effect on the gasifier reactor operating temperatures, and the rate of decrease in reactor temperature escalates at higher pressures. Therefore control of reactor pressure is also necessary if optimum temperature is to be achieved.

IV. Recommendations

From the above studies, the following recommendations are made:

- Almost all the studies above involve entrained and fluidized bed gasifiers. Much research need to be done on fixed bed gasifiers to ascertain their operating conditions.
- There is need for enhanced research on gasifiers for small scale applications like for domestic use so that many house holds can use gasification to generate syngas for cooking
- Most of the studies done involve slurry-fed gasifiers. It is therefore necessary for more studies to be done on dry-fed gasifiers to understand their characteristics and applications.
- Given the importance of temperature and pressure in gasification processes, regulation of gasifier heat is very necessary. More research is necessary on simpler but effective ways of regulating reactor heat for small scale gasifiers like use of water jackets.
- Most of the data available are based on the use of pure oxygen - steam, or air -steam or carbon dioxide-steam as the gasifying agents. More studies should be done on the use of steam - oxygen-enriched air as the oxidizing agents.

V. Conclusion

It has been shown that feed oxygen and water concentrations have a direct influence on the quality and quantity of syngas produced from a gasifier. It has also been verified that temperature and pressure in the gasifier reactor affects the performance and efficiency of the gasifier.

Increasing oxygen supply to gasifier increases the reactor temperature, cold gas efficiency, and gas calorific value. It also enhances production of carbon monoxide and carbon conversion rate leading to enhanced syngas yield. Increasing steam concentrations in the gasifier reduces gas caloric value, enhances yield in hydrogen and methane but reduces reactor temperature.

Increase in gasifier temperature enhances syngas yield, gas calorific value and cold gas efficiency. But it also increases carbon dioxide and oxides of nitrogen that are not desirable in a gasification process.

Acknowledgment

We acknowledge the staff and managements of Jomo Kenyatta University of Agriculture and Technology and the Technical University of Mombasa for their support by allowing the authors to use their research facilities and resources to accomplish this review.

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