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Effects of Different Gasifying Agents on Synthesis Gas Composition from Fluidized Bed Gasification using Raw and Torrefied Wood Sawdust

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Gasification of raw and torrefied wood sawdust were performed in fluidized bed gasifier using three different gasifying agents namely air, steam and oxygen. The effects of different gasifying agents on synthesis gas composition, yield of synthesis gas and lower heating value (LHV) were investigated at various gasification temperature from 650 to 1100 °C. Based on gasification experimental results, raw wood sawdust from steam gasification produces the highest hydrogen gas composition (31.5%) at temperature of 850 °C followed by 30.9% hydrogen composition from oxygen gasification and gasification using air as agent only manage to produce around 18.1% hydrogen composition. Meanwhile the highest synthesis gas yield of 2.52 Nm^3/kg and LHV of 9.31 MJ/Nm^3 are obtained from torrefied wood sawdust using oxygen as gasifying agent. This indicates steam is preferable as gasifying agent for producing hydrogen rich in synthesis gas. Meanwhile torrefied biomass from oxygen gasification is feasible for obtaining higher yield and energy content of synthesis gas.

1. Introduction

Gasification is one of the wastes to energy approaches for producing synthesis gas from biomass (Tezer et al., 2022). Gasification is normally performed at high temperatures (>600 ºC) with the employment of gasification agents such as air, carbon dioxide, steam, oxygen and combinations one or two agents (Ramos et al., 2018). The selection of gasifying agents are significant in order to produce high quality synthesis gas. Among gasification agents, air is widely used in gasification process due to its abundant resource and simple to employ. For example, gasification of hazelnut shells and municipal sludge were performed using air as gasifying agent in downdraft gasifier where gas produced can be utilized further for power generation (Ayol et al., 2019; Midilli et al., 2001). Meanwhile steam as gasification agent is preferable since its ability to produce hydrogen rich synthesis gas with high calorific value (Watson et al., 2018). Steam is dominantly used as a reactant during steam reforming and water-gas shift reactions which producing high amount of hydrogen (Hernandez et al., 2012). Oxygen is another option for gasifying agent. Oxygen gasification produces the highest heating value compared to steam and air gasifications (Tezer et al., 2022). During gasification, oxygen acts as oxidizing agent which contributes to the increment of carbon conversion for producing more hydrogen and carbon monoxide and directly increase the energy content of product gas.

Although different gasifying agents including air, steam and oxygen were used for gasification process but most of the works performed gasification study based on single gasifying agent and only limited work can be found on comparison of synthesis gas composition from different gasifying agents. However, most of the works found related to different gasifying agents study are based on simulation works such as the use of thermodynamic equilibrium model or Aspen simulation model (Islam, 2020; Shayan et al., 2018). Although both models can be used to reasonably predict synthesis gas composition but both have inherent limitations compared to experimental work particularly in accurately capturing complex and dynamic nature of gasification process. Thus, it is essential to perform gasification experiments for evaluating and comparing the use of different gasifying agents on composition of synthesis gas. In addition, raw biomass as gasification feedstock is widely used in most of biomass gasification study and recently torrefied biomass become attractive alternative to be

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used as gasification feedstock. The main advantages of torrefied biomass compared to raw biomass are low moisture content, high carbon content and high energy density. Thus, torrefied biomass produces high synthesis gas composition and yield compared to raw biomass (Saleh and Samad, 2021; Kuo et al., 2014).
Thus, the effects of different gasifying agents on the synthesis gas composition using fluidized bed gasifier are performed in this work. Three gasifying agents which consists of air, steam and pure oxygen are selected for comparison purposes. Two types of feedstocks are considered which are raw and torrefied wood sawdust at 300 ºC for evaluating the effectiveness of torrefaction as biomass pretreatment. Wood sawdust is chosen as feedstock due to the fact that it is disposed of as landfill or incinerated in burner which contributes to environmental issues. Gasification temperature is varied between 650 and 1100 ºC in order to investigate the influences of gasifying agents on the production of synthesis gas. Furthermore, the yield of synthesis gas and energy content from different gasifying agents are evaluated for raw and torrefied wood sawdust.

2. Materials and methods

2.1 Preparation of wood sawdust sample, torrefaction process and sample analysis

In this study, wood sawdust was obtained from wood processing mill at Kuantan Pahang, Malaysia. The wood sawdust was grinded and sieved for obtaining particle size in the ranges of 0.5 – 1.0 mm. This size was chosen due to ease feedstock loading and optimum rate of heat transfer (Campbell et al., 2019). For torrefaction experiment, 5 g of wood sawdust samples were inserted into the torrefaction reactor. Then nitrogen gas at flow rate of 20 ml/min was used for creating inert conditions in the reactor. The wood sawdust samples were torrefied at temperature of 300°C for 30 min residence time. Finally, the torrefied wood sawdust sample was kept in a desiccator. In terms of sample analysis, proximate analysis in terms of volatile matter, ash and moisture contents were determined based on ASTM E872-82, ASTM 1755-01 and moisture analyser (Model MS-70, A&D Company Ltd., Tokyo, Japan) respectively. Bomb calorimeter (C200, IKA® Works (Asia) Sdn Bhd) was employed for measuring high heating value (HHV) of raw and torrefied wood sawdust. Ultimate analysis for both samples were obtained from CHNS/O elemental analyzer (FlashSmart CHNS/O, Thermo Scientific). Table 1 shows the properties of both wood sawdust.

Table 1: Proximate analysis, ultimate analysis and HHV of raw and torrefied wood sawdust

Properties	Raw Wood Sawdust	Torrefied Wood Sawdust
Proximate analysis (wt%)		
Moisture content	10.15	2.71
Volatile matter	66.08	41.56
Ash content	6.62	16.26
Fixed carbon (by difference)	17.15	39.47
Ultimate analysis (wt%)		
Carbon	52.75	60.03
Hydrogen	6.87	5.77
Nitrogen	1.88	2.93
Oxygen (by difference)	38.34	31.04
Sulfur	0.16	0.23
High heating value (MJ/kg)	19.27	28.66

2.2 Gasification process

Gasification process was performed using fluidized bed reactor as shown in Figure 1. Initially raw wood sawdust was used as feedstock and fed to the reactor at rates between 0.3-0.4 kg/h. Meanwhile air flow rate was fixed at ratio of 0.42 to biomass feedstock. This experiment was performed initially at temperature of 650 °C and was repeated until temperature of 1000 °C based on 50 °C increment. The product gas is then moved out from fluidized bed reactor into cyclone. In the cyclone, solid components such as char is collected at the bottom of the cyclone. Product gas is then undergoing cleaning and drying process for obtaining dry and clean gas. Gas sampling bags are used for product gas collection and analyzed using gas chromatography with thermal conductivity detector (GC-TCD). The experiment was repeated using steam and oxygen respectively where similar ratio of 0.42 to biomass feedstock were used. Similar procedures were then performed for gasification using torrefied wood sawdust for comparing the effects of different agents on synthesis gas composition using raw and torrefied wood sawdust. All experiment works were repeated three times in order to enhance data reliability and the average synthesis gas data was presented.

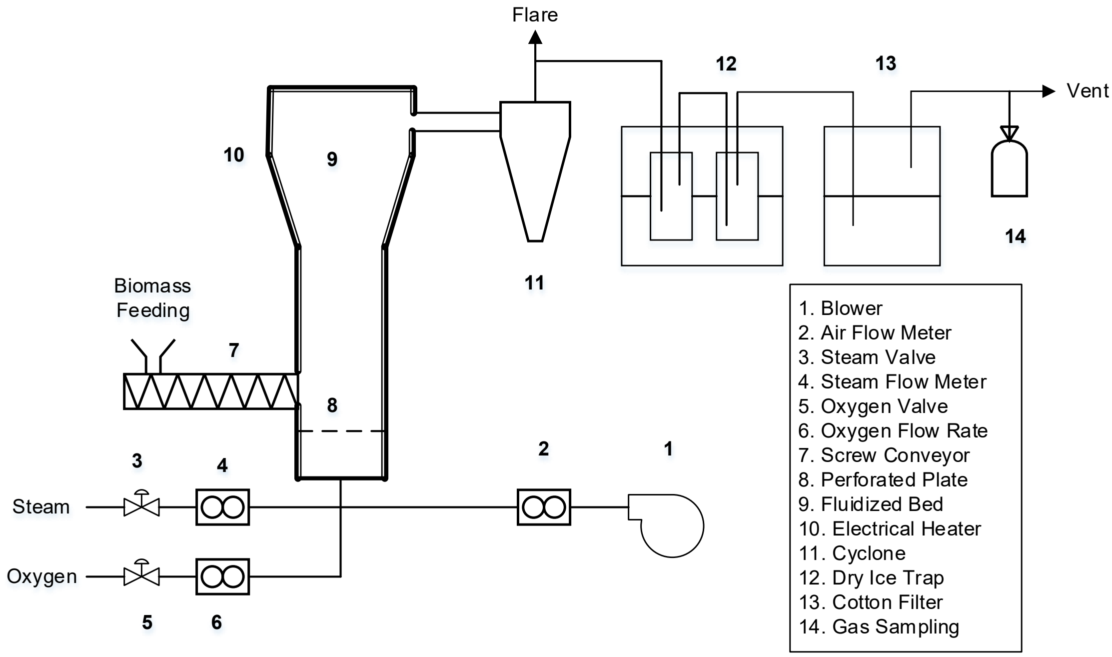

Figure 1: Experimental setup of fluidized bed gasification with different gasifying agents

Synthesis gas yield (Y_{gas}) and lower heating value (LHV) for measuring energy contents of product gas was calculated using Eqs(1) and (2) respectively (Motta et al., 2018).

$$Y_{gas} = \frac{V_{gas}}{\dot{m}_{bio}} \tag{1}$$

Where V_{gas} is the collected amount of synthesis gas and $\dot{m}_{bio}$ is the amount of biomass feed.

$$LHV = (30x_{CO} + 25.7x_{H_2} + 85.4x_{CH_4}) \times 4.2 \tag{2}$$

Where x in Eq(2) are the carbon monoxide, hydrogen and methane gas components in mole fractions.

3. Results and discussions

3.1 Effects of different gasifying agents on the composition of synthesis gas

Effect of air, steam and oxygen as gasification agents on synthesis gas composition for raw and torrefied wood sawdust are shown in Figure 2. The synthesis gas composition obtained from different gasifying agents are compared at various gasification temperatures from 650 to 1100 °C. In overall, it can be observed the hydrogen and carbon monoxide compositions are steadily produced when the gasification temperature is increased for all gasifying agents using both feedstocks. However, it is important to note that hydrogen composition reach maximum values at gasification temperature of 850 °C for all gasifying agents and start to decrease when temperature is greater than 850 °C. On the contrary, carbon dioxide and methane compositions show decrement trends. According to the Le Chatelier's principle, initially at lower temperature the gasification reactions favor the products in endothermic reactions and it shifts to favor the reactants in exothermic reactions at higher temperature (Jamin et al., 2020; Zhou et al., 2009). In terms of composition, steam gasification produce the highest amount of hydrogen around 31.5% at temperature of 850 °C for raw wood sawdust. For steam gasification, more steam is reacted with the feedstock through shift reaction ($C + H_2O \leftrightarrow CO + H_2$) which leads to the increment of hydrogen concentration (Shayan et al., 2018). Figure 2 also shows the highest carbon monoxide composition (43.05%) is produced at gasification temperature of 1100 °C using torrefied wood sawdust when employing oxygen as gasifying agent followed by steam (25.88%) and air (17.78%) respectively. This is due to the fact that oxygen is reacted through oxidation reaction ($C + O_2 \leftrightarrow CO_2$) which produces more carbon dioxide. Subsequently, carbon dioxide is further reacted through Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$) to produce carbon monoxide and this explain the decrement trends of carbon dioxide composition for all gasifying agents.

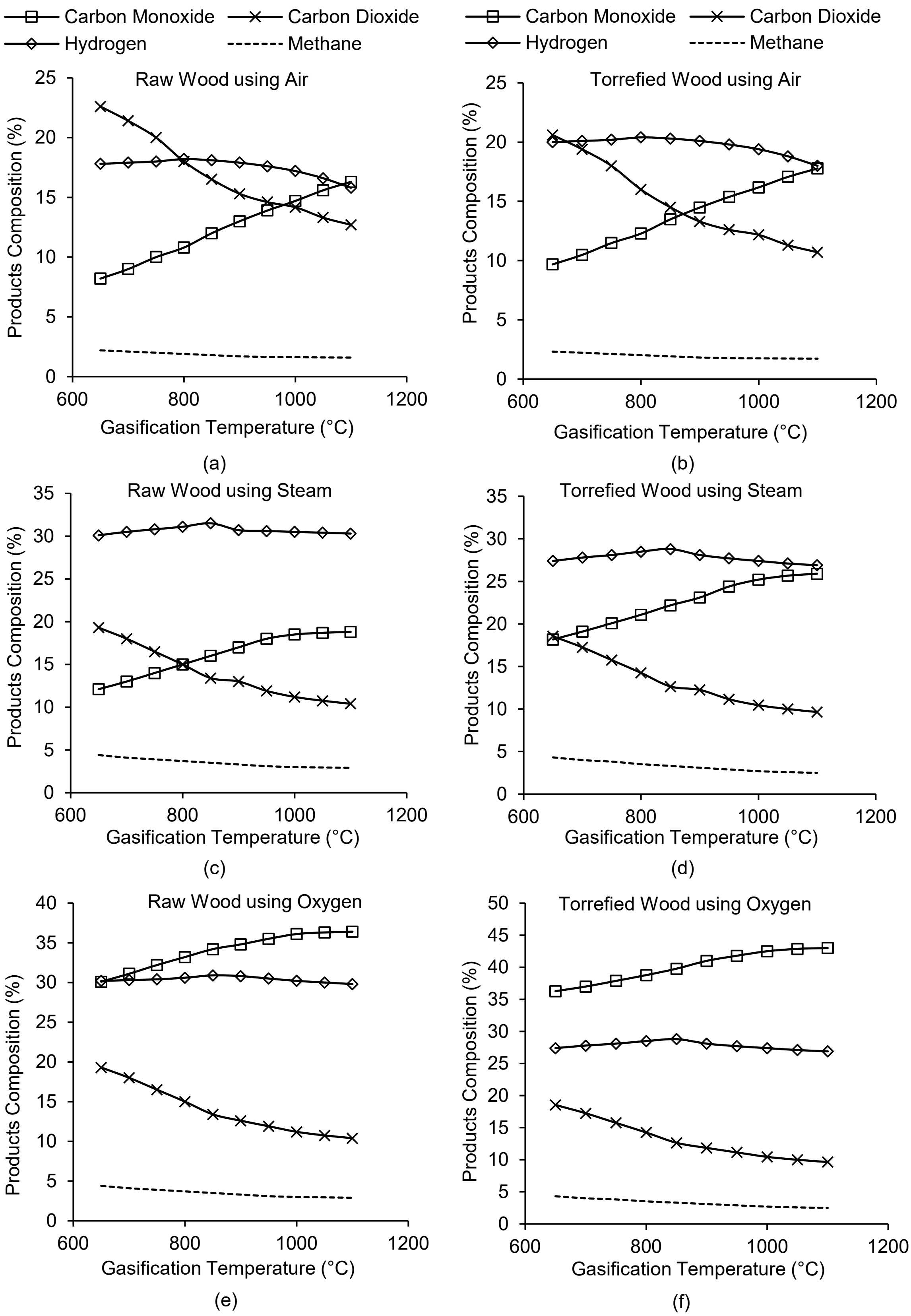

Figure 2: Effects of various gasifying agents on products composition for (a) raw wood sawdust from air gasification, (b) torrefied wood sawdust from air gasification, (c) raw wood sawdust from steam gasification, (d) torrefied wood sawdust from steam gasification, (e) raw wood sawdust from oxygen gasification and (f) torrefied wood sawdust from oxygen gasification

Meanwhile, methane compositions from all gasifying agents show steady decrement at all temperatures for both feedstocks. Usually, methane gas is produced due to the methanation reaction ($C + 2H_2 \leftrightarrow CH_4$) but it is subsequently consumed through methane dry reforming reaction ($CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$) which explain the slight decrement of methane gas composition at all temperatures for both feedstocks (Halim et al., 2019; Lahijani and Zainal, 2011). In terms of gasifying agents, it can be concluded that steam is preferable for producing the highest hydrogen, oxygen can be used as gasifying agent for carbon monoxide production and air as gasifying agent produces the lowest synthesis gas composition compared to other. For feedstocks comparison, torrefied wood sawdust produces lower hydrogen gas and higher carbon monoxide gas from all gasifying agents' experimental results compared to raw wood sawdust. As shown in Table 1, torrefied wood sawdust contains higher carbon content but low hydrogen content compared to the raw wood sawdust which ultimately contributes to more carbon monoxide production and less hydrogen production for torrefied wood sawdust gasification.

3.2 Effects of different gasifying agents on synthesis gas yield and lower heating value

The effect of different gasifying agents on synthesis gas yield and lower heating value for raw and torrefied wood sawdust was conducted by varying gasification temperatures from 650 to 1100 °C. Figure 3(a) shows the increment of synthesis gas yield for all gasifying agents (raw and torrefied wood sawdust). The increment of synthesis gas yield is dominantly contributed by increase amounts of hydrogen and carbon monoxide due to shift and Boudouard reactions. Torrefied wood sawdust using oxygen as gasifying agent shows the highest synthesis gas yield compared to other gasifying agents and raw wood sawdust. This is due to the fact that oxygen is actively reacted during oxidation reaction to produce carbon dioxide which subsequently undergo Boudouard reaction for producing more carbon monoxide which represents major proportions in synthesis gas yield.

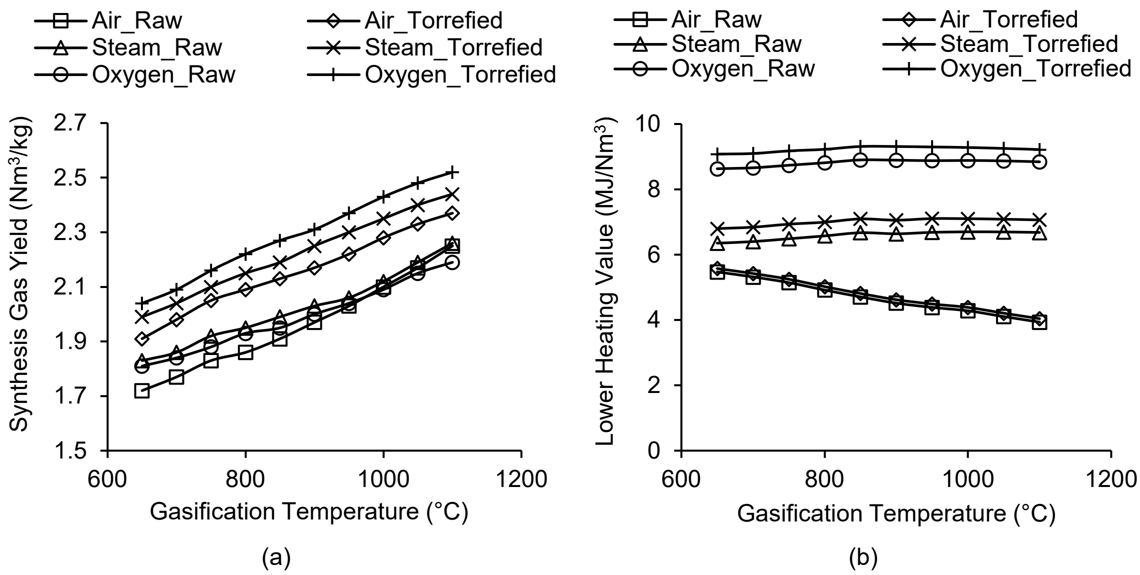

Figure 3: Effects of different gasifying agents using raw and torrefied wood sawdust on (a) synthesis gas yield and (b) lower heating value

Meanwhile, the effects of different gasifying agents on LHV is shown in Figure 3(b). LHV for both raw and torrefied wood sawdust from steam and oxygen gasification shows steady increment as gasification temperature is increased. The increment of hydrogen and carbon monoxide compositions directly increase LHV since both compositions are used for LHV calculation as indicated in Eq(2). Meanwhile LHV raw and torrefied wood sawdust from air gasification shows decreasing trends. The amount of both carbon monoxide and hydrogen compositions from air gasification are relatively lower compared to the compositions produced from steam and oxygen gasification. This contributes to decrement trends of LHV for both raw and torrefied wood sawdust in the case of air gasification. This suggests a disadvantage of using air as gasifying agent since it requires a high biomass flow rate for improving LHV of product gas (Shayan et al., 2018). In addition, the use of torrefied wood sawdust as feedstock for gasification process provides significant advantage when using steam/oxygen as gasifying agents. Torrefied wood sawdust produces higher synthesis gas yield and LHV particularly when oxygen is employed as gasifying agent. Torrefied wood sawdust possess better carbon content compared to raw wood sawdust due to torrefaction process which contributes to high carbon monoxide production from oxidation reaction. This directly improves synthesis gas yield and LHV from oxygen gasification.

4. Conclusions

Synthesis gas composition comparison from raw and torrefied wood sawdust from fluidized bed gasification were performed using air, steam and oxygen as agents at different gasification temperatures between 650 to 1100 °C. Based on synthesis gas composition, hydrogen gas was increased and reach its maximum values at gasification temperature of 850 °C and was decreased afterwards. The highest hydrogen gas (31.5%) was obtained from raw wood sawdust using steam as gasifying agents. Meanwhile carbon monoxide composition steadily increased when the temperature was increased. In this case, torrefied wood sawdust obtained the highest carbon monoxide composition (43.05%) at gasification temperature of 1100 °C using oxygen as gasifying agent. In addition, oxygen gasification using torrefied wood sawdust produces the highest synthesis gas yield around 2.52 Nm^3/kg at gasification temperature of 1100 °C and the highest LHV of 9.31 MJ/Nm^3 at gasification temperature of 850 °C. Based on this work, it can be concluded that steam is best to use for hydrogen rich production and oxygen is preferable for improving synthesis gas yield and LHV. However, it is important to note external heat source is required for operating steam gasification at high temperature since endothermic reactions are expected when steam is used as gasifying agent. Meanwhile, oxygen as gasifying agent contributes to exothermic reactions through partial combustion and thus eliminates the needs for an external heat source in order to sustain high temperature conditions during gasification process but the main limitation of using air as gasifying agent is it has significant economic implications involving cost of oxygen production.

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