

Catalytic Gasification of Empty Oil Palm Fruit Bunches Using Iron and Aluminum Metal Pillared Bentonite Catalysts to Produce Environmentally Friendly Fuel Gas

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ABSTRACT

Indonesia is a country that has abundant natural resources such as palm oil, coal and so on. These two types of coal mining and palm oil plantation sectors have provided many benefits for community welfare. The aims of research is to utilize palm oil industry waste in the form of empty fruit bunch (EFB) and fine coal waste (FCW) into synthetic gas (syngas) through a catalytic gasification process which is then used as a source of energy and/or synthesis chemicals. Gasification temperatures are 450 °C, 550 °C and 650 °C. Gasification time 20, 30 and 40 minutes. The ratio between pillared bentonite catalyst and EFB is 0.125 and 0.25. The resulting syngas is analyzed for the content of H₂, CO, CH₄ and CO gases. At gasification temperatures of 450 °C, 550 °C and 650 °C, the H₂/CO gas ratio is 1.90; 2.05 and 2.27. The increase in this ratio is not very significant, because the increase in the H₂/CO ratio increases only 19.47% from a temperature of 450 °C to a temperature of 650 °C. The comparison value between combustible gas (H₂, CO and CH₄) and non-combustible gas (CO₂), namely the CG/NCG ratio shows the quality of a syngas. The higher the CG/NCG value, the better syngas is as a gas fuel because it has a higher heating value. The CG/NCG value at a temperature of 450 °C is 14.18, while at a temperature of 550 °C it is 17.16 and at 650 °C it is 21.41. With an increase in temperature from 450 °C to 650 °C the increase in CG/NCG value is 51%. Therefore, by increasing the CG/NCG value, the quality of the syngas will increase and the calorific value of burning the syngas will improve. The HHV value at a temperature of 450 °C is 8.34 MJ/Nm³, at a temperature of 550 °C is 12.32 MJ/Nm³ and at a temperature of 650 °C is 15.53 MJ/Nm³. Thus, increasing the temperature from 450 °C to 650 °C, there is an increase in HHV of 86.21%. This result is economically beneficial because the increase in calorific value will increase the benefits of syngas. The higher the HHV value, the better the syngas is used as gas fuel. The HHV value at a temperature of 450 °C is 7.49 MJ/Nm³, at a temperature of 550 °C is 11.06 MJ/Nm³ and at a temperature of 650 °C is 13.91 MJ/Nm³. Thus, by increasing the gasification temperature from 450 °C to 650 °C, there is also an increase in LHV of 85.71%, meaning it has increased quite significantly. When compared with the use of 0.125% catalyst, the increase in catalyst concentration of 0.25% is smaller than 91.90%. From the experimental results it can be concluded that increasing temperature will improve the quality of syngas. Improving the quality of syngas can be done through the syngas enrichment process through the conversion of CO₂ gas reacting with carbon to produce CO gas. The concentration of CO₂ gas can be reduced by absorbing CO₂ gas by the Ca(OH)₂ solution.

Keywords: gasification, bentonite, metal pillared syngas.

INTRODUCTION

Indonesia is a country that has abundant natural resources such as palm oil, coal and so on. South Sumatra Province is one of the largest oil palm and coal producing areas. These two types of coal mining and palm oil plantation sectors have provided many benefits for community welfare. However, these two types of activities will produce waste which will have a negative impact if not controlled. Through science and technology input, these negative impacts can be reduced and can even have positive impacts. The palm oil industry processes fresh fruit bunches (FFB) to produce crude palm oil (CPO). This industry also generates large amounts of solid waste in the form of lignocellulosic compound residues. Palm oil FFB contains around 21% palm oil, the remainder includes 23% EFB [1]. Total CPO production in Indonesia reached 45.581 million tons with a land area of 14.99 million Ha [2]. In 2022, the amount of EFB waste was around 10.483 million tons. EFB contains the main components of cellulose, hemicellulose and lignin which are C5 and C6 polymers. EFB has a very high water content of up to 60% [3] due to the ripening process to separate the fruit. Direct use of EFB as fuel will increase the risk of air pollution because it produces carbon monoxide gas due to incomplete combustion [4]. EFB in several industries only piles up empty bunches in the open area of the factory for quite a long time and this will cause greenhouse gases. The obstacles or challenges that will be faced in implementing gasification on a large scale in Indonesia are the competition for the use of raw materials as an energy source in the boiler to generate electricity through combustion.

Fine coal waste (FCW) is residue/solid waste generated from the coal processing process with particle sizes ≤ 0.5 mm [5]. FCW produces 30% of total coal production. Indonesia is one of the largest coal producers in the world, where in 2023, according to the Ministry of Energy and Mineral Resources, total coal production in Indonesia reached 775.2 million tons, so FCW in Indonesia was 232.56 million tons. In the mining industry, FCW is dumped into ponds and this will cause environmental problems so it needs to be utilized.

Therefore, this proposed research is to utilize palm oil industry waste in the form of EFB and FCW into synthetic gas (syngas) through a catalytic gasification process which is then used as a source of energy and/or synthesis chemicals such

as methanol, diatom ether and others. The catalyst used is bentonite which is widely available in Indonesia. This bentonite will be activated and pillared by the metal. Syngas obtained from gasification will be enriched and purified so that high quality syngas will be obtained (high levels of H_2 , CO and CH_4).

Biomass as a fuel source

Biomass is organic material produced from green plants, which can be obtained from the photosynthesis process, which ultimately forms biomass [6]. In Indonesia, the potential for biomass as an energy source can reach 49 GW, it can be used as renewable biofuel. Biomass is very profitable because it is very abundant and can be converted into bioenergy. Utilization of bioenergy can reduce the use of fossil energy and achieve national energy security [7]. Several studies have been carried out on the use of EFB, such as for briquette raw materials, bioethanol using hydrolysis and fermentation processes [8,9] which produces around 74.43% ethanol. EFB is also used as a catalyst in making biodiesel from CPO to produce 91% biodiesel [10]. EFB is converted into fuel through fast pyrolysis and liquefaction. The obstacle faced in the conversion of EFB to bio-oil is that it is susceptible to the formation of carbon deposits and is more corrosive than petroleum [11]. EFB can be converted into gas fuel through gasification, using a gasification medium. Chew et al. [12] used CO_2 and steam for the gasification process of EFB that had been corrected. EFB is combined with sewage sludge using the SCWG method at 400 °C and 25 MPa [13]. The research results show that the addition of EFB has a synergistic effect on syngas production from sewage sludge and EFB in supercritical water.

Fine coal waste

According to Borowski and Hycnar [14], fine coal waste (FCW) has a fine coal calorific value ranging from 20–23 MJ/kg with an ash content of 58 to 69%, while fixed carbon and sulfur according to Parzentny and Róg, [15] respectively amount to 21.52% and 1.13%. In the metal industry, cement and small-scale power generation companies, FCW is used as raw material for making briquettes for energy fuel and poses a risk of causing air pollution by releasing CO_2 gas, sulfur and fly ash. The high ash content in

FCW is dominated by silica and alumina minerals as the main mineral components in fine coal [16]. FCW is generated in *coal mining and coal stockpile*.

Gasification

Gasification is the process of changing carbon raw materials such as biomass, coal, into thermochemical gases (CO , H_2 and CH_4) which have high calorific value [17] with the help of a gasification medium. in the form of air, steam, oxygen, carbon dioxide or a mixture of them [18, 19]. The resulting gas is called synthesis gas or synthetic gas or syngas. This syngas can be used for fuel, electricity generation and raw materials for chemical manufacturing processes in industry [20]. The composition of the gas produced is influenced by several factors such as the type of raw material, operating conditions, type of gasifier and gasification medium. The success of the gasification process is also assessed from the lower heating value (LHV) of the gas, carbon conversion efficiency (CCE) and cold gas efficiency (CGE) [12]. The CO content increases slowly with a range of 20–30 mole% at 450–650 °C. When the gasification temperature reaches 700 °C, the CO concentration is reduced by 6.5 mole% to 19 mole% at the end of the process [21]

Stages of the gasification process

In a gasifier, 4 sub processes occur, namely heating and drying, pyrolysis, oxidation or combustion and reduction. The H_2 and CO_2 content in the gas increases while the CO and CH_4 content decreases as the steam to biomass (S/B) ratio increases. The performance of gasification using air is very dependent on temperature and equivalent ratio (ER). Oxygen is often used as a gasification medium because of its ability to produce gases of moderate calorific value compared to air, where the carbon conversion efficiency and H_2 and CO content are higher [22]. Oxygen is often combined with steam as a gasification medium by Sharma and Sheth [23] and Ismail et al. [24].

Catalytic gasification

The use of catalysts in gasification can increase reaction speed and reduce operating temperatures. Catalysts can break atomic bonds in molecules which causes the molecules to split and

have a charge [25, 26]. Several types of heterogeneous catalysts are used for biomass gasification such as the metals Ni, Pd, Ru, Rh, Pt, Ni and also Co [26]. The use of the $\text{NiO}/\text{Al}_2\text{O}_3\text{-CaO}$ catalyst in EFB supercritical gasification increases hydrogen and reduces CO_2 along with the addition of the catalyst [25]. Our research group has carried out EFB gasification at a temperature of 350–550 °C using a natural bentonite catalyst, which was thermally activated at a temperature of 400 °C for 3 hours, producing syngas with an H_2 content of 27.74% mol, CO 20.43% mol at a temperature of 550 °C. The heating values of HHV and LHV are 3.38–12.79 MJ/Nm³ and 3.03–12.58MJ/Nm³ respectively. Maximum carbon conversion efficiency (CCE) and coal gas efficiency (CGE) are 85.49% and 82.34% respectively [27]. The results of this research are not yet optimal, so the proposed research is needed using a metal pillared bentonite catalyst, followed by an enrichment and purification process. The use of 12.5% wt natural zeolite as a catalyst in EFB gasification has also been carried out at temperatures of 350–550 °C. The best results occurred at 550 °C with a composition of 22.64% vol CH_4 , 29.22% vol CO, and 3.4% vol H_2 , with CGE and CGE values of 95.74% and 81.65% respectively. [28]. We researchers have also carried out FCW catalytic gasification using bentonite (catalyst/FCW ratio 0–0.25) at 550–750 °C). The highest composition was obtained at 750 °C, with a composition of 42.6 vol% H_2 , 19.1 vol% CO, 19.5 vol% CH_4 , and 7.9 vol% CO_2 . The best performance is if the catalyst/FCW ratio is 0.25 where the composition is 54.3 vol% H_2 , 26.2 vol% CO, 23.8 vol% CH_4 , and 3.5 vol% CO_2 , the heating value and gasification efficiency are respectively 19.72 MJ/ Nm³ and 72.27% at 750 °C [29]. Syngas purification has also been carried out where CO_2 gas is absorbed by the $\text{Ca}(\text{OH})_2$ solution with an absorption percentage of 50.63% [30].

Natural catalyst for the gasification process

Natural bentonite is a lamellar aluminosilicate mesoporous material that has a crystalline structure. The interlayer space in the structure is occupied by replaceable cations, for example Na^+ , K^+ , Ca^{+2} [31]. The characteristics of bentonite depend on the amount of smectite. The properties of smectite namely cation exchange capacity, particle size, pore structure, adsorption properties, surface area and catalytic activity

are greatly influenced by thermal treatment [32]. Bentonite from smectite, especially montmorillonite (80-90%wt) which when montmorillonite comes into contact with water can expand several times its original volume [33]. Calcium bentonite was proven to be a catalyst for plastic pyrolysis [34]. Bentonite is able to increase bio-oil yield compared to other natural clays and synthetic zeolites in switchgrass pyrolysis [35]. According to The Indonesia Mine and Coal Research and Development Center 2017, the current confirmed reserves of bentonite in Indonesia is estimated at the total number of 380 million tons.

Bentonite can act as a catalyst in thermochemical processes such as pyrolysis [35], cracking [36], biodiesel manufacturing processes [37, 38] and gasification. In the pyrolysis process, the addition of bentonite can increase the yield [39]. This statement is supported by Sewu et al. [40] that bentonite increases bio oil up to 35% from microalgae pyrolysis. Bentonite can act as a solid base catalyst in the conversion of glucose to lactic acid [41] which is from 5% to 11%. Ro et al. [42] stated that bentonite has a positive effect on the pyrolysis of lignin to produce low char. Bentonite contains metal oxides that are rich in SiO_2 so that it has an oxygenate removal effect and an inhibitory effect on coke formation on the catalyst [39]. Research on catalytic cracking in transformer oil by Kar et al. [43] provided significant results using bentonite as a catalyst. From a yield of 92.09% wt of oil without catalyst, there was an increase in yield to 98.64% wt (with a ratio of 4% bentonite). Gasification using steam has the potential for the production of hydrogen-enriched syngas, especially with a CaO catalyst and at temperatures suitable for high H_2 production [44, 45, 46]. Syngas from biomass steam gasification with a CaO catalyst is increasingly enriched in H_2 [47], where the higher the temperature, cellulose content and hydrogen-carbon ratio and steam to biomass (S/B) ratio, the higher the hydrogen production. The use of CaO causes CO_2 adsorption ($\text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3$) and reduces the partial pressure, which is favorable for the WGS reaction to increase H_2 [45].

Kinetic model of gasification

In order to understand the entire gasification process, it is very important to analyze the reaction kinetics and thermodynamics. Some methods, for example, use triplet kinetic parameters which can be calculated from thermogravimetric

analysis. Where the change in mass with increasing temperature at a certain heating rate is measured [47]. The triplet kinetic parameters consist of activation energy, pre-exponential factor, and reaction model [48–50]

MATERIAL AND METHODS

Gasification procedure

Gasifier (fixed bed type), cylindrical form of stainless steel. The gasifier is insulated to avoid heat loss. The gasifier is equipped with two flow pipes to enter the gasification agent and an output pipe for the synthetic gas product. 5 kg of fine EFB waste is added from the feed hole. A flowmeter is installed to measure the flow rate of the gasification agent (air/oxygen). The air/oxygen flow rate is set at 10 l/minute. The pressure of gasification process is atmospheric. In this gasification process, the experimental parameters are gasification time and gasification temperature. Gasification temperatures are 450 °C, 550 °C and 650 °C. Gasification time 20, 30 and 40 minutes. The ratio between pillared bentonite catalyst and EFB is 0.125 and 0.25. The resulting syngas is analyzed for the content of H_2 , CO, CH_4 and CO gases, and other hydrocarbon organic compounds.

FCW carbonization

The fine coal used is under 3 mm in size and is supplied by coal mining at PTBA. Carbonization temperature is 500 °C for 1 hour. The carbon obtained is used for enrichment, syngas. Syngas obtained from the gasifier is reacted with carbon from coal, so that CO_2 gas is converted into CO gas. at temperatures of 450 °C, 550 °C and 650 °C. Syngas resulting from the enrichment process is analyzed for H_2 , CO, CH_4 and CO_2 gas content. Syngas from the enrichment process is purified (purified) using a lime solution ($\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$) in a reactor/absorber. CO_2 will react with the Ca(OH)_2 solution to form a CaCO_3 precipitate. This purified syngas is then analyzed for gas content H_2 , CO, CH_4 and CO_2 .

RESULTS AND DISCUSSION

Table 1 shows the experimental results of the gasification process in the form of syngas

Table 1. Syngas composition, H₂/CO ratio value, CG/NCG ratio, and syngas combustion value both HHV and LHV, in the EFB gasification process using 0.125% metal pillared bentonite catalyst

Temperature, °C	Syngas					Other gas	CG/ NCG	H ₂ /CO	Heat value	
	H ₂	CO	CH ₄	CO ₂	Total				HHV (MJ/Nm ³)	LHV (MJ/Nm ³)
450	23.5	12	7.9	3.1	46.5	53.5	14.00	1.96	7.66	6.88
550	33.1	15.7	12	3.21	64.01	35.99	18.94	2.11	10.99	9.86
650	46.2	18.9	16.1	3.79	84.99	15.01	21.42	2.44	14.70	13.14

composition, H₂/CO ratio value, CG/NCG ratio, and syngas combustion value both HHV and LHV, in the EFB gasification process using a 0.125% metal pillared bentonite catalyst.

Composition in units of mole percent (%mole) of synthesis gas components (H₂, CO, CH₄ and CO₂ and other gases) formed from the EFB catalytic gasification process using metal pillared bentonite (concentration 0.125% by mass), at a gasification temperature of 450 °C, 550 °C and 650 °C. From the results of this research, there was an increase in the concentration of each synthetic gas (syngas) with increasing temperature. At a temperature of 650 °C, at a temperature of 650 °C the concentration of H₂ gas reaches 46.2% mol, CO gas reaches 18.9% mol, CH₄ gas reaches 16.1% mol and CO gas reaches 3.79% mol. Meanwhile, other gases were the lowest at 15.01% mol. The calorific value of this synthetic gas is determined by the concentration of combustible gas, namely H₂, CO and CH₄ gas. It is hoped that by increasing the concentration of combustible gas, the calorific value of the syngas obtained will be better. From the results of this research, the comparison of combustible gas with non-combustible gas reached the highest value, namely 21.42 at a gasification temperature of 650 °C. By increasing the gasification temperature, the endothermic reaction will shift to the right of the reaction equation so that it will increase the combustibility of the gas as in the reaction:

- $C + H_2O \leftrightarrow CO + H_2$ (Reforming char),
- $CO + H_2O \leftrightarrow CO_2 + H_2$ (Water gas shift reaction),
- $C + 2H_2 \leftrightarrow CH_4$ (Methanation reaction),
- $H_2 + 1/2O_2 \rightarrow H_2O$ (Hydrogen oxidation),
- $CH_4 + H_2O \leftrightarrow CO + 3H_2$ (Steam and methane reaction),
- $CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ (Dry reforming methane).

The formation of hydrogen gas occurs due to the right-hand reaction from the char reforming reaction, the water gas shift reaction, the reaction between CH₄ and water vapor and from the dry

reforming reaction of methane. On the other hand, hydrogen gas decreases when methanation reactions and hydrogen oxidation reactions occur. The increase in syngas at a temperature of 650 °C reached 84.99%.

The formation and/or increase in carbon monoxide gas occurs from partial oxidation reactions, Boudouard reactions, steam formation from methane and dry reforming of methane, while the decrease in H₂ gas is caused by the water gas shift reaction.

The concentration of CO gas, which is also a combustible gas, increases with increasing temperature. At temperatures of 450 °C, 550 °C and 650 °C, the CO concentration was 12% mol, 15.7% mol, 18.9% mol or an increase of 57.5%, respectively, from a temperature of 450 °C to 650 °C. Based on data for methane gas (CH₄), the concentration of this gas increased from 7.9 mole% at a temperature of 450 °C to 16.1 mole% at a temperature of 650 °C, which means an increase of 103.8%. This increase is quite significant. The formation of methane gas is triggered by the methanation reaction, while the decrease in methane gas is caused by the reaction of steam and methane as well as the methane dry reforming reaction. In the gasification process, the presence of CO₂ gas is not desired or is kept to a minimum. This CO₂ gas cannot be burned (non-combustible). For this reason, the presence of CO₂ gas can be converted into combustible CO gas through the Boudouard reaction ($CO_2 + C \rightarrow 2CO$).

It would be better for these two reactions to shift to the right so that the CO₂ gas concentration decreases and at the same time can enrich the CO gas in the syngas. At gasification temperatures of 450 °C, 550 °C and 650 °C, the concentration of CO₂ gas increases from 3.2% mol, to 3.21% mol and then to 3.79% mol. This increase is not very significant, because the increase in CO₂ gas concentration increased by only 22.2%. It can be seen that with increasing gasification temperature, the H₂/CO ratio will increase, although not too

significantly. At gasification temperatures of 450 °C, 550 °C and 650 °C, the H₂/CO gas ratio is 1.96; 2.11 and 2.44. The increase in this ratio is not very significant, because the increase in the H₂/CO ratio increases only 24.49% from a temperature of 450 °C to a temperature of 650 °C.

The quality of a syngas can be seen from the comparison value between combustible gas (H₂, CO and CH₄) and non-combustible gas (CO₂), namely the CG/NCG ratio. The higher the CG/NCG value, the better syngas is as a gas fuel because it has a higher heating value. The CG/NCG value at a temperature of 450 °C is 14.00, while at a temperature of 550 °C and 650 °C it is 18.94 and 21.42 respectively. With an increase in temperature from 450 °C to 650 °C the increase in CG/NCG value is 53%. In other words, by increasing the CG/NCG value, the quality of the syngas will increase and the calorific value of burning the syngas will improve. The HHV values at temperatures of 450 °C, 550 °C and 650 °C are 7.66 MJ/Nm³, 10.99 MJ/Nm³ and 14.70 MJ/Nm³, respectively. Thus, with an increase in temperature from 450 °C to 650 °C, there is an increase in HHV of 91.90%, meaning the faith has doubled. This result is economically beneficial. The higher the HHV value, the better the syngas is used as gas fuel. The LHV values at temperatures of 450 °C, 550 °C and 650 °C are 6.88 MJ/Nm³, 9.86 MJ/Nm³ and 13.14 MJ/Nm³, respectively. Thus, by increasing the gasification temperature from 450 °C to 650 °C, there is also an increase in LHV of 91.90%, meaning it has doubled.

Gasification of EFB with metal pillared bentonite catalyst at a concentration of 0.25%

Table 2 below shows the experimental results of the gasification process in the form of syngas composition, H₂/CO ratio value, CG/NCG ratio, and syngas combustion value both HHV and LHV, in the EFB gasification process using a 0.25% metal pillared bentonite catalyst. From the results of the EFB gasification experiment using a

metal pillared bentonite catalyst concentration of 22.5%, there was an increase in the concentration of each synthetic gas (syngas) with increasing temperature. At a temperature of 650 °C, the concentration of H₂ gas reaches 46.9 mole %, CO gas reaches 20.7 mole %, CH₄ gas reaches 17.4 mole % and CO₂ gas reaches 3.97 mole %. Meanwhile, other gases were the lowest at 11.03% mol. The calorific value of this synthetic gas is determined by the concentration of combustible gas, namely H₂, CO and CH₄ gas. It is hoped that by increasing the concentration of combustible gas, the calorific value of syngas, both HHV and LHV values obtained, will be better. From the results of this research, the comparison of combustible gas with non-combustible gas (CG/NCG) reached the highest value, namely 21.41 at a gasification temperature of 650 °C. By increasing the gasification temperature, the endothermic reaction will shift to the right of the reaction equation so that it will increase the combustibility of the gas as in the reaction:

From the series of reaction equations above, the concentration of syngas components will increase or decrease depending on which reaction is faster and the equilibrium value that has been reached. In the char reforming reaction, CO and H₂ gas will increase. In the water gas shift reaction, CO gas will decrease but H₂ gas will be formed. In the methanation reaction, there will be an addition of methane gas but a decrease in H₂ gas, while in the hydrogen oxidation reaction the level of H₂ gas will decrease. In the steam and methane reaction, there was an increase in the content of CO gas and H₂ gas, but there was a decrease in CH₄ gas. In the methane dry reforming reaction, there was also an increase in the content of CO gas and H₂ gas, but there was a decrease in CH₄ gas.

The hydrogen gas content will increase due to the right-hand reaction from the char reforming reaction, the water gas shift reaction, the reaction between CH₄ and water vapor and from the dry reforming reaction of methane. On the other

Table 2. Syngas composition, H₂/CO ratio value, CG/NCG ratio, and syngas combustion value both HHV and LHV, in the EFB gasification process using 0.25% metal pillared bentonite catalyst

Temperature, °C	Syngas					Other gas	CG/NCG	H ₂ /CO	Heat Value	
	H ₂	CO	CH ₄	CO ₂	Total				HHV (MJ/Nm ³)	LHV (MJ/Nm ³)
450	25.40	18.10	9.20	1.50	54.20	45.80	35.13	1.40	9.19	8.32
550	36.10	19.70	15.40	1.20	72.40	27.60	59.33	1.83	13.23	11.90
650	47.10	22.30	20.00	0.90	90.30	9.70	99.33	2.11	16.79	15.07

hand, hydrogen gas decreases when methanation reactions and hydrogen oxidation reactions occur. An increase in syngas from a temperature of 450 °C to a temperature of 650 °C caused an increase of up to 88.35%.

The carbon monoxide content in syngas will increase due to the partial oxidation reaction, Boudouard reaction, steam formation from methane and dry reforming of methane, while the decrease in H₂ gas is caused by the water gas shift reaction. The concentration of CO gas, which is also a combustible gas, increases with increasing temperature. At temperatures of 450 °C, 550 °C and 650 °C, the CO concentration is 13.1% mol, 17.1% mol, and 20.7% mol or from a temperature of 450 °C to 650 °C. There is an increase in CO gas levels of 58.02%,

From the experimental results, for methane gas (CH₄), the concentration of this gas increased from 8.8% mol at a temperature of 450 °C to 17.4% mol at a temperature of 650 °C, which means an increase of 97.73%. This increase is quite significant. The formation of methane gas is increased by the methanation reaction, while the decrease in methane gas is caused by the steam and methane reaction as well as the methane dry reforming reaction. In the catalytic EFB gasification process, the presence of CO₂ gas is not desired or is kept to a minimum. This CO₂ gas cannot be burned (non-combustible). To reduce CO₂ gas and convert it into CO gas which is a combustible gas, you can use the Boudouard reaction ($\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$). This stage is carried out in order to increase CO gas and reduce CO₂ gas in syngas.

Therefore, efforts must be made to shift the two reactions above as little as possible to the right, so that the formation of CO gas is minimal. At gasification temperatures of 450 °C, 550 °C and 650 °C, the concentration of CO₂ gas increased from 3.3% mol, to 3.87% mol and then to 3.97% mol. This increase is not very significant, because the increase in CO₂ gas concentration increased by only 20.3%. It can be seen that with increasing gasification temperature, the H₂/CO ratio will increase, although not too significantly. At gasification temperatures of 450 °C, 550 °C and 650 °C, the H₂/CO gas ratio is 1.90; 2.05 and 2.27. The increase in this ratio is not very significant, because the increase in the H₂/CO ratio increases only 19.47% from a temperature of 450 °C to a temperature of 650 °C.

The comparison value between combustible gas (H₂, CO and CH₄) and non-combustible gas

(CO₂), namely the CG/NCG ratio shows the quality of a syngas. The higher the CG/NCG value, the better syngas is as a gas fuel because it has a higher heating value. The CG/NCG value at a temperature of 450 °C is 14.18, while at a temperature of 550 °C it is 17.16 and at 650 °C it is 21.41. With an increase in temperature from 450 °C to 650 °C the increase in CG/NCG value is 51%. Therefore, by increasing the CG/NCG value, the quality of the syngas will increase and the calorific value of burning the syngas will improve. The high CG/NCG value will be more profitable, because the selling value of high-calorie fuel will increase profits in its production.

The HHV value at a temperature of 450 °C is 8.34 MJ/Nm³, at a temperature of 550 °C is 12.32 MJ/Nm³ and at a temperature of 650 °C is 15.53 MJ/Nm³. Thus, increasing the temperature from 450 °C to 650 °C, there is an increase in HHV of 86.21%. This result is economically beneficial. The higher the HHV value, the better the syngas is used as gas fuel. The HHV value at a temperature of 450 °C is 7.49 MJ/Nm³, at a temperature of 550 °C is 11.06 MJ/Nm³ and at a temperature of 650 °C is 13.91 MJ/Nm³. Thus, by increasing the gasification temperature from 450 °C to 650 °C, there is also an increase in LHV of 85.71%, meaning it has increased quite significantly. When compared with the use of 0.125% catalyst, the increase in catalyst concentration of 0.25% is smaller than 91.90%.

CONCLUSIONS

From the experimental results it can be concluded that increasing temperature will improve the quality of syngas. Improving the quality of syngas can be done through the syngas enrichment process through the conversion of CO₂ gas reacting with carbon to produce CO gas. The concentration of CO₂ gas can be reduced by absorbing CO₂ gas by the Ca(OH)₂ solution. Recommendations for optimal temperature of gasification is 650 °C.

Acknowledgments

This research was financially supported by Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia through Penelitian Dasar Kompetitif Nasional scheme (Grant Number: 142/E5/PG.02.00.PT/2022 and 0148.011/UN9.3.1/PL/2022).

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