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Effects of Oxygen Enrichment in Air Oxidants on Biomass Gasification Efficiency and the Reduction of Tar Emissions

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Abstract: This study applied oxygen-enrichment conditions to remove tar (the main problem in biomass gasification) and increase gasification efficiency. Experiments on oxygen-enrichment conditions were conducted at oxygen concentrations of 21%, 25%, 30%, and 35% in oxidants. This was expected to increase the partial oxidation reaction in gasification reactions, thus leading to thermal decomposition of tar in producer gas. The decomposed tar was expected to be converted into syngas or combustible gases in the producer gas. The results were as follows: Tar-reduction efficiency was 72.46% at 30% oxygen enrichment compared to the standard 21% enrichment condition. In addition, the concentrations of syngas and combustible gases in the producer gas tended to increase. Therefore, the 30% oxygen-enrichment condition was optimal, resulting in 78.00% for cold gas efficiency and 80.24% for carbon conversion efficiency. The application of oxygen enrichment into the lab-scale gasification system clearly reduced the concentration of tar and tended to increase some indexes of gasification efficiency, thus suggesting the usefulness of this technique in large-scale biomass gasification operations.

Keywords: biomass; gasification; tar; oxygen enrichment; syngas

1. Introduction

Factors such as industrial development and population growth have resulted in various negative environmental consequences, including accelerated climate change and fossil fuel depletion. Indeed, increased greenhouse gas concentrations have resulted in abnormal weather conditions and an average annual temperature rise. Climate change has also rapidly increased as a result of CO₂ from fossil fuel emissions. For this reason, alternative energy development research is a worldwide concern. Biomass research is also relatively easy to conduct while studying new and renewable energy sources across a variety of fields. Applying biomass to the thermal treatment process can produce similar results to the CO₂ generated and consumed for growing. Such research can contribute to carbon neutrality and aid in sustainable development to prevent climate change. The term “biomass” collectively refers to wood, waste wood, agricultural crops and their byproducts, municipal solid waste, animal waste, waste from food, and aquatic plants and algae [1,2]. Due to these characteristics, it is used in various fields (e.g., pyrolysis and gasification) and is known for its relatively stable energy yields [2,3].

The gasification process has been highlighted as a technology that can replace incineration, which is the traditional thermal recovery process. The main purpose of gasification is the production of chemical products through synthetic gases and electricity [4]. Gasification is primarily accomplished using coal as a fossil fuel, and some biomasses and wastes have been commercialized [5]. Gasification

is known to involve a relatively complex chemical reaction compared to that of the incineration process. Stable operation is thus difficult. Table 1 shows the main chemical reactions resulting from gasification [6].

Table 1. Chemical reactions resulting from gasification [6].

Stoichiometry	Standard Heat of Reaction (kJ/mol)	Name	Number
Biomass $\rightarrow$ char + tar + H_2O + light gas ($CO + CO_2 + H_2 + CH_4 + C_{2+} + N_2 + \dots$)	Endothermic	Biomass de-volatilization	R1
<i>Char combustion</i>			
$C + 1/2O_2 \rightarrow CO$	−111	Partial combustion	R2
$C + O_2 \rightarrow CO_2$	−394	Complete combustion	R3
<i>Char gasification</i>			
$C + CO_2 \rightarrow 2CO$	+173	Boudouard reaction	R4
$C + H_2O \rightarrow CO + H_2$	+131	Steam gasification	R5
$C + 2H_2 \rightarrow CH_4$	−75	Hydrogen gasification	R6
<i>Homogeneous volatile oxidation</i>			
$CO + 1/2O_2 \rightarrow CO_2$	−283	Carbon monoxide oxidation	R7
$H_2 + 1/2O_2 \rightarrow H_2O$	−242	Hydrogen oxidation	R8
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	−283	Methane oxidation	R9
$CO + H_2O \leftrightarrow CO_2 + H_2$	−41	Water gas-shift reaction	R10
<i>Tar reactions (tar assumed C_nH_m)</i>			
$C_nH_m + (n/2)O_2 \rightarrow nCO + (m/2)H_2$	Endothermic (except R11) (200–300)	Partial oxidation	R11
$C_nH_m + nCO_2 \rightarrow (m/2)H_2 + (2n)CO$		Dry reforming	R12
$C_nH_m + nH_2O \rightarrow (m/2 + n)H_2 + nCO$		Steam reforming	R13
$C_nH_m + (2n-m/2)H_2 \rightarrow nCH_4$		Hydrogenation	R14
$C_nH_m \rightarrow (m/4)CH_4 + (n-m/4)C$		Thermal cracking	R15

The carbon and hydrogen feedstock used in the gasifier are converted into high heating value gases such as H_2 , CO , CH_4 , and heavy hydrocarbon gases. As previously stated, more stable operation technology is required to apply gasification using new and renewable energies. Biomass and waste products require advanced technology, especially when compared to coal.

Woody biomasses are most often used during the biomass gasification process. However, they contain lignin component compared to other kinds of feedstock, such as coal. Typically, wood is composed of about 25% lignin, and 70% cellulosic carbohydrates, with roughly 45% cellulose and 25% hemicellulose [7]. Lignin which acts as a bonding agent for hydrocarbon products is the main cause of tar production. Generally, tar formed during the gasification process cause three problems. First, it results in condensation and a subsequent plugging of the downstream equipment. Second, it produces tar aerosols. Third, associated polymerization results in a more complex structure [8–10]. It is, therefore, necessary to reduce tar generation [11]. Tars indicate the existence of undesirable gasification byproducts and heavy hydrocarbons with molecular weights higher than benzene [12]. Tar can be classified in various ways. For instance, tar can be divided into primary, secondary, and tertiary types based on its appearance. Based on its molecular weight, tar can also be placed into one of five classes. Table 2 shows the classification of tar based on its appearance, while Table 3 shows the classification of tar based on molecular weight. Such tar can be divided into condensable and non-condensable. Condensable tars can cause serious damage, such as cracking in filter pores, coke formation and plugging, and condensation in cold spots, thus resulting in serious interruption to several processes, including those of the cleaning and power generation facilities. Condensable tar is classified as pollutants that must be removed from producer gas [13].

Table 2. Classification of tar based on its appearance [9,10].

Tar Class	Property
Primary	Low molecular weight oxygenated hydrocarbons such as levoglucosan, furfural and hydroxyacetaldehyde, produced at 400–700 °C
Secondary	Phenolic and olefin compounds such phenol, cresol, and xylene, produced at around 700–850 °C
Tertiary	Aromatic compounds such as benzene, naphthalene, pyrene, and toluene, produced at around 850–1000 °C

Table 3. Classification of tar based on molecular weight [9,10].

Tar Class	Property
Class 1	GC undetectable heaviest tars which condense at high temperature and very low concentration
Class 2	Heterocyclic aromatic compounds which are high water solubility such as pyridine, phenol, cresols, quinoline, isoquinoline, and dibenzophenol
Class 3	Light hydrocarbon aromatic compounds (1 ring) which do not cause a problem regarding condensability and solubility such as toluene, ethylbenzene, xylenes, styrene
Class 4	Light polyaromatic hydro carbon compounds (2–3 rings) which condense at low temperature even at very low concentration such as indene, naphthalene, methylnaphthalene, biphenyl, acenaphthalene, fluorine, phenanthrene, anthracene
Class 5	Heavy polyaromatic hydrocarbon compounds (4–7 rings) which condense at high temperature at low concentration such as fluoranthene, pyrene, chrysene, perylene, coronene

Tar reduction during the gasification process is largely accomplished in one of two ways (i.e., the in situ or post-gasification methods). The in situ method reduces tar control during gasification reactions in the gasifier. This involves forming, thermal cracking, steam cracking, and controlling operating conditions (e.g., temperature, pressure, residence time, and gasification oxidant). On the other hand, post-gasification tar reduction does not interfere with the gasifier process. Post-gasification reduction includes various physical processes involving cyclones, wet scrubbers, and electrical precipitators in addition to chemical processes (i.e., the thermal and catalytic) and partial oxidation. Figure 1 shows the two major tar-reduction methods [14,15].

Figure 1. The two major tar-reduction methods. (a) In situ tar reduction (primary reduction); (b) Post-gasification tar reduction (secondary reduction).

This study employed an operating condition using in situ tar reduction during the gasification process. Operating costs were therefore relatively cheap. Air was used as an oxidant; oxygen was simultaneously injected to control the oxygen-enrichment conditions. The experiments were conducted at oxygen concentrations of between 21% and 35%. Oxidation reactions were enhanced by increasing oxygen levels in the air while maintaining equivalent ratio (ER), a major factor in gasification. These enhanced oxidation reactions were able to increase the endothermic reaction during the gasification reaction and accomplish tar reduction by partial oxidation and thermal cracking. It is undesirable to apply thermal cracking to tar at high temperatures to promote the decomposition of large organic molecules into smaller non-condensable gases without a catalyst. This is because the process requires energy and produces soot [9,16]. However, in this study, it was possible to apply thermal cracking to tar by altering the oxygen concentration without using additional energy.

2. Materials and Methods

The hardwood sawdust used in this study was selected to represent woody biomasses. It was considered to ease the supply and demand in addition to the Lab-scale gasification system application. For the gasification process, the physicochemical characteristics of the feedstock were necessary to control operational conditions. An elementary analysis (EA), proximate analysis (PA), heating value analysis (HVA), and thermo-gravimetric analysis (TGA) were conducted based on American Society for Testing and Materials (ASTM) guidelines.

The EA involved a qualitative analysis on organic feedstock elements such as C, H, N, O, S, and Cl. EA can be used to predict flue gas and pollutant concentrations when deducing process design factors. An oxidizing element is injected into both the gasification and incineration processes. This is essential for determining the amount of oxidizing agent. EA was performed using EA 1112 and EA 1110 instruments according to ASTM D5373 (according to ASTM International (2016), these are standard test methods for determining the levels of carbon, hydrogen, and in-analysis samples of coal and coke) instructions [17,18].

A PA was used to acquire data for quantitative moisture, volatile matter, fixed carbon, and feedstock ash. These are the most appropriate criteria for determining the applicability of the thermal treatment processes. Lower levels of moisture and ash are generally applied to the thermal treatment process, while higher compositions of volatile matter and fixed carbon can recover energy. The PA was performed using a TGA 701 instrument according to ASTM D3172 instructions (according to ASTM International (2013), this is standard practice for conducting a proximate analysis of coal and coke) [17–19].

An HVA was used to obtain the objective heating value per unit weight of feedstock. Higher heating values mean that less main and auxiliary fuels can be used during the thermal treatment process. This is an important factor for ensuring economic feasibility. The HVA was performed using an AC 600 instrument according to ASTM D4809 instructions (according to ASTM International (2013), this is a standard test method for determining the combustion heat for liquid hydrocarbon fuels using a bomb calorimeter) [17,20].

Finally, the TGA provided a visual overview of the feedstock's thermal properties. This is possible even when interpreting the PA. The biomass decomposition temperature can be divided into hemicellulose, cellulose, and lignin temperatures. Hemicellulose decomposes at 220–315 °C, cellulose at 315–400 °C, and lignin at 315–400 °C. Lignin generally tends to decrease gradually and slowly decomposes up to 900 °C [21]. The TGA results are thus important for finding the appropriate temperature, PA results, and chemical composition for biomass feedstock. The TGA was performed using a TGA 701 instrument according to ASTM E1131 instructions (according to ASTM International (2008), this is a standard test method for conducting a compositional analysis using thermogravimetry) [17,22].

This study used a lab-scale gasification system with a capacity of 2 g/min, including a downdraft and fixed-bed gasifier for relatively easy operation. Figure 2 shows a schematic diagram of the

lab-scale gasification process used in this study. The gasifier was heated using an electric furnace (the temperature was maintained at a constant level during the experiment). A semi-batch was made for the feeding system and the gasifier was maintained and operated at negative pressure for stable feeding. A dual-tube type gasifier was used, which could be divided into inner and outer tubes. Producer gas flow was designed to downdraft. The gas cleaning system consisted of a cyclone for fly ash removal, wet scrubber for the removal of dust and water-soluble gaseous pollutants in the producer gas, and bag filter to protect the analyzer from dust and moisture. After moisture removal, producer gas flow was analyzed using a dry gas meter. A micro-GC (specifically, a 3000 Micro-GC from INFICON co.) and real-time analyzer could be performed once every five minutes to increase data reliability. The micro-GC was able to analyze for O_2 , CO , CO_2 , H_2 , CH_4 , N_2 , C_2H_6 , and C_3H_8 , while the real-time analyzer was used for O_2 , CO , CO_2 , H_2 , and CH_4 . Micro-GC is known as an essential analyzing device for measuring producer gases generated during the gasification process. The device maintains high accuracy (i.e., approximately 5 to 500 ppm). Tar sampling was also conducted at one sampling port located at the exits of the gasification system.

Figure 2. Schematic diagram of the lab-scale gasification process.

The ER maintained an experimental value of 0.3 considering general operating conditions of the gasification plant ranged from ER 0.2 to 0.5 [23,24]. In the feeding system, biomass was fed into the gasifier with a semi-batch type and maintained at a feeding rate of 2 g/min. The oxygen was injected at the same value for all conditions; Oxygen-enrichment conditions were adjustable by reducing the amount of air input and increasing the amount of oxygen input. The optimum temperature (i.e., 900 °C) was applied to the TGA result among all physicochemical characteristics. The experiment temperature was maintained by referring to the gasifier's internal TC 1 temperature and using the electric furnace as a lab-scale gasification system. Also, enrichment conditions were controlled to achieve basic oxygen conditions of 21% (2.34 L/min air), 25% (1.87 L/min air and 0.04 L/min oxygen), 30% (1.49 L/min air and 0.19 L/min oxygen), and 35% (1.16 L/min air and 0.25 L/min oxygen). These oxidant mixtures were controlled by 21%, 25%, 30%, and 35% of the oxidant resulting from holding the oxygen input amount (0.49 L/min oxygen) at ER 0.3. We also chose to reduce the amount of air injected because the percentage of pure oxygen increased, thereby resulting in oxygen-enrichment conditions while maintaining the absolute amount of oxygen injected into the gasifier. Lastly, these experiments were conducted once for each condition. However, the tar-sampling results and gasification characteristics (e.g., producer gas composition) involved data retrieved from stable operational sections.

Generally, the tar analysis method can be divided into the processes of cold solvent trapping (CST), solid phase adsorption (SPA), and the on-line tar analyzer. CST was sampled for 100 to 1000 L of a gas when passed through a series of impingers containing an ice-cooled solvent. Samples were then analyzed using GC-MS [25]. SPA was sampled for 100 mL of a producer gas that was passed through

a disposable cartridge (e.g., activated carbon). We were then able to calculate weight or analyze using GC-MS. The on-line tar analyzer was used based on a comparison of the total hydrocarbons, which were measured with a flame ionization detector [26]. In this study, CST and SPA were used with activated carbon for tar sampling and analysis. Isopropyl alcohol was used as a solvent for the CST method. Figure 3 shows the sampling train of tar in the producer gas. The order in which gases were passed through was 1→2→4→3→5→6; the 1, 2, and 3 impingers were set in a heated bath, the temperature was set to 35 °C, and the 4, 5, and 6 impingers were set in a cold bath [27]. The sampling flow rate was 30 L. Sampling was conducted at 1 L/min for 30 min. This absorbent liquid of oxygen enrichment at conditions of 21% and 30% were analyzed using GC-MS (Shimadzu 2010 plus) with 16 types of heavy hydrocarbons, including C₆ to C₁₆. This was done to the tar emitted during the gasification process, which included benzene toluene xylene (BTX) and polynuclear aromatic hydrocarbons (PAHs) [28]. Table 4 shows information on the tar analyzed in this study [15].

Figure 3. Tar-sampling train (European tar protocol).

Table 4. Classification of tar resulting from gasification (C₆–C₁₆) [15].

Tar	Chemical Formula	Molecular Weight	Boiling Point (°C)
Benzene	C ₆ H ₆	78.1	80.0
Toluene	C ₇ H ₈	92.1	110.6
Pyridine	C ₅ H ₅ N	79.1	115.2
Phenylacetylene	C ₈ H ₆	102.1	143.0
Styrene	C ₈ H ₈	104.1	145.0
Xylene	C ₈ H ₁₀	106.0	138.5
Phenol	C ₆ H ₆ O	94.0	181.8
Benzonitrile	C ₆ H ₅ CN	103.1	190.7
Indene	C ₉ H ₈	116.2	182.0
Naphthalene	C ₁₀ H ₈	128.2	217.9
1-Methylnaphthalene	C ₁₁ H ₁₀	142.2	244.7
Biphenylene	C ₁₂ H ₈	152.2	280.0
Fluorene	C ₁₃ H ₁₀	166.2	295.0
Phenanthrene	C ₁₄ H ₁₀	178.2	340.0
Fluoranthene	C ₁₆ H ₁₀	202.0	393.0
Pyrene	C ₁₆ H ₁₀	202.0	393.0

The SPA was conducted using a fixed-bed type adsorber with activated carbon, which is an excellent adsorbent. A previous study reported higher measurement efficiency for light tar when compared to the CST sampling method. However, the sampling efficiency of both light and heavy PAH compounds using the SPA method was lower than that obtained through the CST sampling method; these tars may have condensed before sampling due to the low sampling temperature [29]. Following these advantages and disadvantages alike, CST is more efficient than the SPA method. However, the SPA method was not expected to result in major issues in this study because of the need

for tar-reduction trends using the oxygen-enrichment conditions. Table 5 shows the characteristics of the activated carbon used in this study. The Brunauer-Emmett-Teller (BET) theory may have had the greatest effect on the analysis showing that the surface area was $1150 \text{ m}^2/\text{g}$ [17]. In this study, tar in the producer gas was analyzed using both CST and SPA sampling methods for data crosschecking purposes.

Table 5. Activated carbon characteristics.

Specification	Activated Carbon	
Size distribution	mm	$5\% \leq 4.2, 95\% > 4.2$
Hardness	%	≥ 90
Bulk density	g/mL	0.47–0.52
Iodine adsorptive power	mg/g	≥ 950
Benzene adsorptive power	mg/g	≥ 35
Pressure loss	-	Low
Spontaneous combustion temperature	$^{\circ}\text{C}$	400–500

The efficiency indices for evaluating the gasification process include the cold gas efficiency (CGE), carbon conversion efficiency (CCE), and gas yield (Gy) [30–32]. CGE is a percentage of the low heating value of gas (LHV_{gas}) input by the total $\text{LHV}_{\text{feedstock}}$ input, which shows the efficiency of the most important factor during thermal treatment processes. LHV_{gas} is calculated based on the amount of heat produced when the producer gas is completely combusted. CCE is an index of how much of the C component in the feedstock has been converted into carbon-based gases, thus indicating efficiency in the chemical reaction between the feedstock and the injected oxidant. This CCE shows changes in various factors, including the type of feedstock, oxidation, and gasifier. Finally, Gy is an index of the volume of generated gases per unit of feedstock input, which is used in the CGE and CCE calculations and should be measured essentially. The calculations of LHV_{gas} , CGE, CCE, and Gy are shown in Equations (1)–(4), as follows:

$$\text{LHV}_{\text{gas}} (\text{kcal}/\text{Nm}^3) = (\text{CO} \times 30.35 + \text{H}_2 \times 24.70 + \text{CH}_4 \times 85.70 + \text{C}_2\text{H}_6 \times 153.80 + \text{C}_3\text{H}_8 \times 223.50) \quad (1)$$

$$\text{CGE}(\%) = \frac{\text{LHV}_{\text{gas}} (\text{kcal}/\text{Nm}^3) \times \text{Gy} (\text{m}^3/\text{kg})}{\text{LHV}_{\text{feedstock}} (\text{kcal}/\text{kg})} \times 100 \quad (2)$$

$$\text{CCE}(\%) = \frac{12 \times \text{Gy} \times (\text{CO} + \text{CO}_2 + \text{CH}_4 + 2 \times \text{C}_2\text{H}_6 + 3 \times \text{C}_3\text{H}_8)}{22.4 \times \text{C}_{\text{feedstock}}} \times 100 \quad (3)$$

$$\text{Gy} (\text{Nm}^3/\text{kg}) = \frac{\text{Producer gas flow rate} (\text{Nm}^3/\text{hr})}{\text{Input feedstock feeding rate} (\text{kg}/\text{hr})} \quad (4)$$

3. Results and Discussions

3.1. Physicochemical Characteristics of Feedstock

Table 6 shows the results of the EA, PA, and HVA. As previously stated, this study used the results of two biomass types (excluding sawdust), which were also used to represent woody biomasses [33–35]. The physicochemical characteristics of the sawdust used in this study were very similar to those of other biomasses. Overall, the range of error was within 5% on average. These results indicated that the sawdust was appropriately representative of woody biomass.

Figure 4 shows the TGA results for the sawdust, which indicated significant reduction sections at 100°C and $300\text{--}400^{\circ}\text{C}$. The first reduction section refers to moisture removal, while the second refers to a de-volatilization section. The appropriate temperature could also be verified by finishing the feedstock reaction in the range of 900°C .

Table 6. Physicochemical characteristics of sawdust and other biomasses.

Analysis	Categories	Sawdust	PKS *	EFB **	Sawdust (ref)
EA (wt. %)	C	45.66	44.60	41.81	45.93
	H	5.81	6.50	5.73	6.65
	N	0.11	2.92	0.84	0.68
	O	45.32	40.20	37.36	46.00
	S	ND ***	0.1	ND	0.16
	Cl	ND	ND	ND	ND
PA (wt. %)	Moisture	3.19	5.92	9.63	6.27
	Volatile matter	78.57	71.31	64.95	78.11
	Fixed Carbon	17.09	17.81	19.48	15.04
	Ash	1.15	4.96	5.94	0.58
HVA (Higher Heating Value, MJ/kg)		16.08	18.51	16.95	17.62

* PKS = Palm Kernel Shell; ** EFB = Empty Fruit Bunch, *** ND = Not Detected.

Figure 4. TGA results for sawdust. (a) TG curve; (b) DTG (Derivative TG) curve.

3.2. Gasification Characteristics

Figure 5 shows composition of the producer gas according to changes in oxygen enrichment. As oxygen enrichment increased, the concentration of syngas ($H_2 + CO$) increased, showing a maximum of 47.64% at the 30% condition. Apart from N_2 and CO_2 , all combustible gases showed an increasing trend. This tendency was due to an increase in other gas compositions as the N_2 in the injected oxidants decreased. When considering the production of chemical products (the aim of which was to increase the composition of syngas before the gasification process), sufficient applicability could be confirmed through the oxygen-enrichment conditions. Syngas composition and LHV_{gas} showed very similar tendencies. The tendency of LHV_{gas} was also due to the relatively reduced composition of nitrogen in the producer gas in addition to the increase in combustible gases.

Figure 5. Composition and LHV of the producer gas.

Figure 6 shows the compositions of C_2H_6 and C_3H_8 . These are heavy hydrocarbon gases and were expected to have similar emission tendencies to the tar emitted from the gasification process. With increased oxygen enrichment, the C_2H_6 and C_3H_8 compositions in the producer gas had similar tendencies to other combustible gases. This tendency is likely due to a phenomenon in which heavy hydrocarbon gases are partially crushed by enhancement of the oxidation reaction because of increased oxygen enrichment. This phenomenon is thus thought to potentially control tar in the producer gas.

Figure 6. C_2H_6 and C_3H_8 compositions in the producer gas.

Figure 7 shows gasification efficiencies for CGE, CCE, and Gy. CCE and Gy decreased with increased oxygen enrichment. By contrast, CGE tended to increase to maximum value at the 30% condition, while CCE and Gy tended to decrease. CGE appeared to result from an increase of syngas compositions and LHV_{gas}. CCE was the result of reduced C_2H_6 and C_3H_8 compositions, which were heavy hydrocarbon gases in the producer gas. However, gasification efficiency at all conditions was satisfied through the general efficiency of the gasification plant (i.e., CGE 65–80% and CCE 70–90%) [36]. In terms of gasification efficiency, CGE had a maximum value of 78.00% and CCE was higher than 80%. This was an optimal condition for 30% oxygen enrichment.

Figure 7. Gasification efficiency trends.

3.3. Emission Characteristics of Tar in the Producer Gas

Tar was analyzed by SPA and CST using activated carbon and isopropyl alcohol, respectively. SPA tar analyses were conducted for all conditions. Tar concentrations tended to decrease drastically as oxygen enrichment increased (i.e., from 65.23 ppm at 35% to 17.97 ppm at 21%). Tar-reduction efficiency was measured at 72.45% at 35% oxygen enrichment. In other research involving biomass gasification, the concentration of tar in the producer gas was measure at 2.6 mg/g at 40% oxygen enrichment; this was the optimum condition [37]. A BET was conducted on the activated carbon

used for tar sampling. Both surface area and pore volume were analyzed to ensure data reliability. The BET analysis revealed a reverse tendency for the surface area of the activated carbon as a result of tar adsorption; a greater amount of generated tar results in increased absorbed by the activated carbon used in the SPA analysis. This results in reduced surface area and pore volume in the activated carbon. Conversely, a lesser amount of tar generated through increased oxygen enrichment results in decreased tar amounts absorbed by the activated carbon. This results in larger surface area and pore volumes. Figure 8 shows the results of the SPA and BET analyses.

Figure 8. SPA and BET analysis results. (a) Tar concentration; (b) BET of activated carbon.

CST tar analyses were conducted at 21% and 30% oxygen-enrichment conditions because the experimental result at 30% oxygen enrichment showed the highest gasification efficiencies for all conditions. In addition, the experimental result at 21% indicated a standard condition using raw air. CST tar analyses were also used to crosscheck the data obtained through the SPA tar analyses. Figure 9 shows the results of the CST tar analysis. The CST results differed from those of the SPA at 21% and 30%. This was thought to result from difficulties in absorbing some tar components, such as gravimetric tar. However, the CST results showed similar trends to those of the SPA. Tar in the producer gas was measured at 82.56 ppm for 21%. Tar at the 30% condition was 22.47 ppm; it was removed at an approximate 72.46% rate of efficiency. Qualitative analysis revealed that most of the tar was composed of benzene (99%) and toluene (approximately 1%) (other components were not detected).

Figure 9. CST tar analysis results.

The results of the CST and SPA tar analyses revealed a relatively similar tendency for the resulting values. However, there was a small difference in the absolute values. At 21% oxygen enrichment, CST shows 82.56 ppm, while SPA shows 65.23 ppm. As previously stated, SPA is more efficient when applied to light tar, but less so for PAH compounds when compared to CST analysis. In this study, the operating temperature was set at 900 °C. This temperature is known to generate increased amounts of light tar when compared to heavy tars such as the PAH compound. For this reason, it was expected

that the concentrations of tar as measured by CST and SPA would not significantly differ. Therefore, tar sampling and analysis during the gasification process at temperatures above 900 °C do not differ significantly when applying either the CST or SPA methods. However, the SPA method is typically more efficient when considering ease of analysis and cost.

Compared with other various tar-reduction technologies, the 72.46% reduction efficiency obtained in this study was quite high. In other tar-reduction technologies, a catalyst results in more than 95% of the total value. However, catalysts involve the disadvantage of high operating costs. It is, therefore, expected that tar-reduction technologies using oxygen enrichment will be sufficiently competitive. Table 7 shows a comparison of the method used in this study with other tar-reduction technologies.

Table 7. Comparison with other tar-reduction technologies.

Methods	Tar Reduction (%)	Reference
Sand bed filter	50–97	[38]
Venturi scrubber	50–90	[39]
Rotational particle separator	30–70	[39]
Wash tower	10–25	[39]
Wet ESP *	50–70	[40]
Fabric filter	0–50	[39]
Catalytic tar cracker	> 95	[38]

* ESP: Electrostatic Precipitator.

Some of the most important operation factors in the pilot or commercial gasification plant are the operating costs. Oxygen-enrichment conditions will significantly increase these costs. However, tar formed during the gasification process should be controlled by clean-up facilities or other technologies. Even if the process does not involve oxygen enrichment, this is rather economical considering the costs of installing clean-up facilities. Due to the increased gasification efficiency resulting from oxygen-enrichment conditions, this is also expected to apply to pilots or commercial gasification plants. It is thus a good option for both.

4. Conclusions

Regarding gasification efficiency, the most reasonable value was optimal when CGE was 78.00% and CCE was 80.24% at the 30% condition. Also, tar reduction occurring at a reduction efficiency of up to 72.46% through oxygen enrichment was likely due to enhancement of the partial tar oxidation process ($C_nH_m + (n/2)O_2 \rightarrow nCO + (m/2)H_2$). In conclusion, tar-reduction efficiency will continue to increase through this process. Sufficient producer gas is obtainable. However, the 30% oxygen-enrichment condition is considered optimal due to gasification efficiency and economic feasibility. Thus, it is possible to use oxygen-enrichment conditions in pilots or commercial-scale gasification plants.

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