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Co-gasification characteristics of palm oil by-products and coals for syngas production

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Abstract−Large amounts of empty fruit bunches (EFB) are generated annually during the palm oil manufacturing process; however, they are still treated as waste. In this study, gasification experiments were conducted using EFB in a fluidized bed reactor (throughput=1 kg/hr) at an experimental temperature range of 700 to 1,000 °C to assess the use of EFB as a renewable energy resource. To overcome the issues of an unstable EFB supply, co-gasification experiments using EFB with coal were conducted. The resulting syngas yield was approximately 70 vol%, similar to that from EFB gasification. The heating value of syngas was a magnitude of three-times higher than that of EFB gasification. However, the dry gas yield and cold gas efficiency were lower than those of EFB gasification. A coal mixing rate of 20 wt% and 0.6 of ER would be appropriate conditions for continuous production of stable syngas.

Keywords: Gasification, Bubbling Fluidized Bed (BFB), Palm Mill Wastes, Empty Fruit Bunch (EFB), Co-gasification, Coal

INTRODUCTION

With the recent establishment of a green growth movement in Korea, all potential new and renewable energy sources, including biomass and waste, are being investigated for sustainable energy production in the future. Continuous efforts over the last decade to generate renewable energy from waste and biomass have led to approximately 80% of renewable energy in Korea being produced from waste and biomass. However, the amount of usable biomass in Korea is limited. Hence, a stable supply of biomass and the development of conversion technologies are essential to fulfill the bioenergy supply plan established by the government [1-3]. Generation of byproducts from the palm mill industry in Malaysia and Indonesia has recently increased as the demand for palm oil has increased. The empty fruit bunch (EFB), one of these byproducts, is a palm-fiber-waste dumped into the facility after the recovery of palm oil, which occupies over 20 wt% of the fresh fruit bunch (FFB) [4]. If EFB could be utilized in biomass-to-energy plants, such as pyrolysis and gasification plants, it would be a realistic alternative resource for sustainable energy generation. The technologies used to produce alternatives to fossil fuel from biomass are classified as biological and thermo-chemical methods. Biological technologies have been developed to generally produce methane and ethanol under anaerobic conditions. The technology for energy conversion from biomass has the advantage of low operating costs because the process is performed at room temperature and a standard atmospheric pressure. However, the reaction time is long and costs are high for treating secondary pollutants [5]. In contrast, not only can thermo-chemical energy conversion technology obtain liquid fuel, but also fuel and solid fuels. It also has the advantage of controlling secondary pollutants. However, the design cost facilities required for this are high [6]. Many studies have been conducted on recovering energy from EFB or coal, and one potential technology for this is syngas production by the gasification of EFB or coal. Pooya et al. [7] conducted a gasification study by considering agglomeration in a bubbling fluidized bed (BFB). Laura et al. [8] conducted co-gasification experiments with coal, plastics, and wood in BFBs. In their study, gasification was conducted as a thermo-chemical technology using a BFB suitable for biomass. It is difficult to guarantee a stable supply of EFB as this material is primarily used as a pellet fuel or fertilizer. Thus, it would be necessary to combine EFB with other supplementary fuels or wastes to buffer against EFB shortages. In this study, co-gasification was conducted using EFB with bituminous coal (low quality) to evaluate the applicability of co-gasification of EFB with coals after determining the optimal conditions of EFB gasification. We only focused on the treatment of EFB and its use as an energy resource. Therefore, the optimal conditions for coal gasification, such as temperature and equivalence ratio (ER), were not considered, and only the experimental values derived from EFB gasification were used.

MATERIALS AND EXPERIMENTAL METHODS

1. Properties of Coal and EFB

EFB was imported from Waris Selesa Sdn. Bhd. in Malaysia. Its initial water content was approximately 60 wt%. The EFB was, therefore, dried for 48 hr at 105 °C, and then was milled and sieved using an ASTM to retrieve EFB particles under 500 μm in size. The EFBs physicochemical characteristics were subsequently examined by thermo-gravimetric (TG), proximate, and elemental analysis, and higher-heating value (HHV) measurement.

Proximate and TG analysis were conducted using a thermogravimetric instrument (Leco, TGA-701). Proximate analysis was

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Table 1. Analytical instruments & methods

Material	Analysis	Instrument	Method
EFB and coals	Elemental analysis	EA1112, Thermo Fischer Scientific	ASTM D 5373 [9]
	Proximate analysis	TGA-701, Leco	ASTM D 3172 [10]
	Thermo-gravity analysis	TGA-701, Leco	ASTM E 1131 [11]
	Higher heating value	AC-600, Leco	ASTM D 4809 [12]

Table 2. Fluidized-bed operating conditions

Parameter	Unit	Value
Capacity	kg/hr	1
Temperature of pre-heater	°C	900 (setting temperature)
Feeding rate	g/min	13
Setting temperature range	°C	700-1,000
Oxygen	L/min	1-2.2
Flow rate of fluidizing gas [N_2]	L/min	15-19
Residence time	Sec	Over 5
Equivalence ratio (ER)	-	0.3, 0.6
Sand	kg	7
Sand density	kg/m^3	1472.73

Table 3. The size distribution of sand (fluidization medium)

Size range of sand (μm)	Under 75	75-250	250-355	355-500	Over 500
Distribution (wt%)	0.3	23.7	59.8	14.4	1.8

subdivided into four components: moisture, volatile compounds, fixed-carbon, and ash. TG analysis monitored weight reduction when the temperature was increased from room temperature (approximately 25 °C) to 950 °C. The weight reduction by thermal heating was analyzed under reducing conditions. The HHV was analyzed using a calorimeter (Leco, AC-600), and elemental analysis was measured by a total of five components (carbon, hydrogen, oxygen, nitrogen, and sulfur) using a Thermo Fischer Scientific analyzer, EA 1112.

Bituminous coal was purchased for the co-gasification experiments, and its physicochemical characteristics were examined using the same instruments that analyzed the EFB. The particle size of the coal was smaller than 300 μm. The coal particles resembled a powder or spheres, whereas the EFB was low density with a thin and long shape. The instruments used for each analysis are described in Table 1.

2. Process of the Fluidized Bed Gasification System

Fig. 1 presents a schematic diagram of the fluidized gasification process used in this study. The process was divided into four zones: pre-heating, reaction, purification, and analyzing zones. In the preheating zone, a pre-heater was installed between the wind box and the gas inlet to reduce the temperature difference when the heating nitrogen gas was colder than room temperature. In the reaction zone, a wind box, which had an inner diameter of 134 mm and height of 100 mm, was installed under the reactor with a bubble cap distributor that had 37 holes. In the reactor, a total of 7 kg of sand was used for applying in-bed feeding. The particle size distribution of the sand is shown in Table 3. Nitrogen gas was used for fluidization of the bed material at a flow rate lower than 20 L/

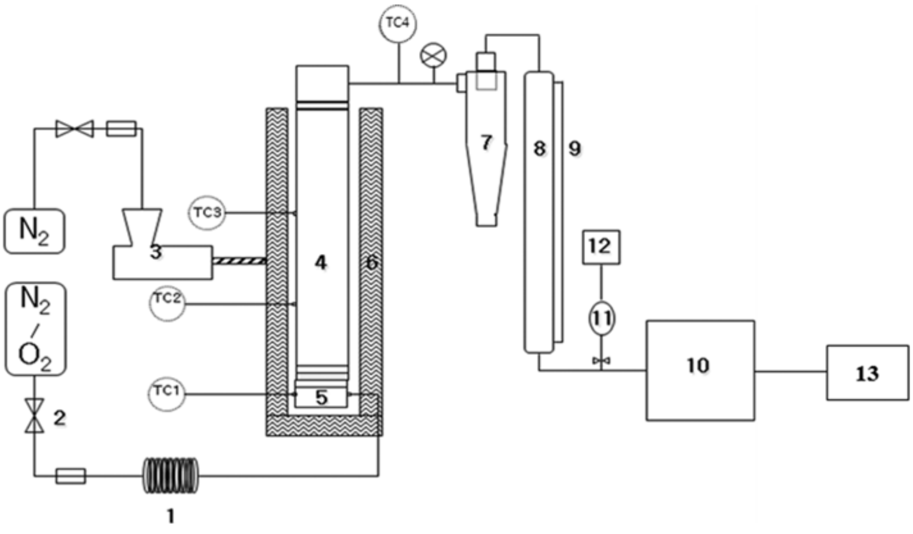


Fig. 1. Process diagram of the fluidized-bed gasification system.

1. Pre-heater	4. Reactor	7. Cyclone	10. Dry gas meter	13. Vent
2. MFC	5. Windbox	8. Scrubber	11. Filter	
3. Screw feeder	6. Furnace	9. Pump	12. Micro-GC	

min (U/U$_{mf}$=1.5). However, the commercial plant had been operated at approximately ER 0.5. The purpose of this research is so that it can be applied to commercial plants in the future. Thus, the ER was 0.3 and 0.6, respectively. The purification zone, which was designed to enhance the removal of particulate pollutants, consisted of a cyclone, scrubber, and filter. Tar was collected from the cyclone, inside reactor, and gas pipe. The weight of the tar was also calculated to use it in mass balance. Finally, several devices, such as the temperature display device and micro-GC, were installed to confirm the temperature change and assess the gas composition in the analyzing zone. A dry gas meter was installed to monitor the produced gas flow. Table 2 shows the fluidized bed gasification conditions, and the gasification process is shown in Fig. 1.

3. Gasification Experimental Conditions

A preliminary EFB gasification experiment was conducted to determine the appropriate gasification temperature and obtain the general conditions of EFB gasification. Then, a co-gasification experiment was conducted under the optimum conditions identified from the EFB gasification experiment. Additionally, in this study, coal was mixed with EFB of up to 30 wt% to determine the optimum ratio of coal to EFB during the co-gasification process. Based on the results of EFB gasification, the temperature range was set to 900 to 1,000 °C. In addition, ER was set to 0.3 and 0.6, which were the same as those in the EFB gasification experiment.

RESULTS AND DISCUSSION

1. Properties of Coal and EFB

From the elemental analysis, EFB was composed of 41.81 wt% carbon, 5.73 wt% hydrogen, 0.84 wt% nitrogen and 37.36 wt% oxygen. These proportions were similar to those in sawdust, although EFB had lower proportions of organic compounds than other biomass types. Sulfur, which could be converted into H_2S during gasification, was not detected. The HHV of EFB was 3,930 kcal/kg. Table 3 contains the results of the analysis.

As the results of EFB elemental analysis were similar to those of other biomasses, these properties indicated that EFB was adequate for use as a biomass fuel [13-15]. To verify this conclusion, the properties of EFB were compared with the properties of other biomasses published in literature. The result of elemental and HHV analysis of EFB were similar to those of sawdust (a type of woody biomass), soybeans, corn straw, palm shells, and Jatropha seed cakes (JSC) [16,17]. The HHV and carbon content of JSC were higher than those of other forms of biomass, with an HHV of 4,952 kcal/kg and approximately 50 wt% carbon. Palm shell, which was obtained from a palm mill byproduct, had higher HHV than the EFB, at 4,406 kcal/kg. When comparing JSC with palm shell, the HHV of the seed byproducts was higher than that of other woody biomass. However, the published values for sawdust were only slightly little higher than that of EFB: 45.93 wt% carbon, 6.65 wt% hydrogen, and 46.00 wt% oxygen, which was approximately 10 wt% higher than that of EFB. Sawdust also contained the highest amount of sulfur; however, this amount was still relatively small. The HHV of sawdust was 4,196 kcal/kg, which was 200 kcal/kg higher than that of EFB. It was concluded that the high carbon, hydrogen, and sulfur content affected these results. The coal used in this study was bituminous, which is low-quality and contains more carbon than biomass. However, it contains a higher amount of sulfur, which can produce H_2S, and has a lower oxygen content than other biomass types. The coal's HHV was two-times higher than that of biomass.

From the proximate analysis, that of EFB consisted of 9.63 wt% moisture, 64.95 wt% volatile compounds, 19.48 wt% fixed-carbon, and 5.94 wt% ash. Volatility is the most important component in biomass pyrolysis technologies because the conversion ratio for producing crude oil increases with increasing volatility [18,19]. Additionally, the water content of EFB was high because it is originally discharged from palm oil processing, which uses high water content, whereas the water content of sawdust was 6.27 wt%. Thus, it was concluded that when the EFB was dried, the drying time, mass, and surface area must be considered. However, the content of volatile compounds in coal was 33.55 wt%, which was lower than that of different biomasses. Table 4 shows the results of the analysis.

The results of TG analysis are an important for setting the experimental conditions, because the characteristics of the feedstock or fuel, such as the temperature of the final reaction, are determined by these results [20]. In this study, TG analysis was conducted under reducing conditions using nitrogen at a heating temperature rate of 10, 20 °C/min. In addition, the EFB TG graph was compared with the results for sawdust as a similar woody biomass to evaluate its applicability as a fuel in thermos-chemical processes. It was concluded that the optimum temperatures for thermo-chemical processes, such as pyrolysis and gasification, were 400 and 900 °C, respectively. During biomass pyrolysis, volatile compounds can easily be converted into vapor at a low temperature. The vapor should

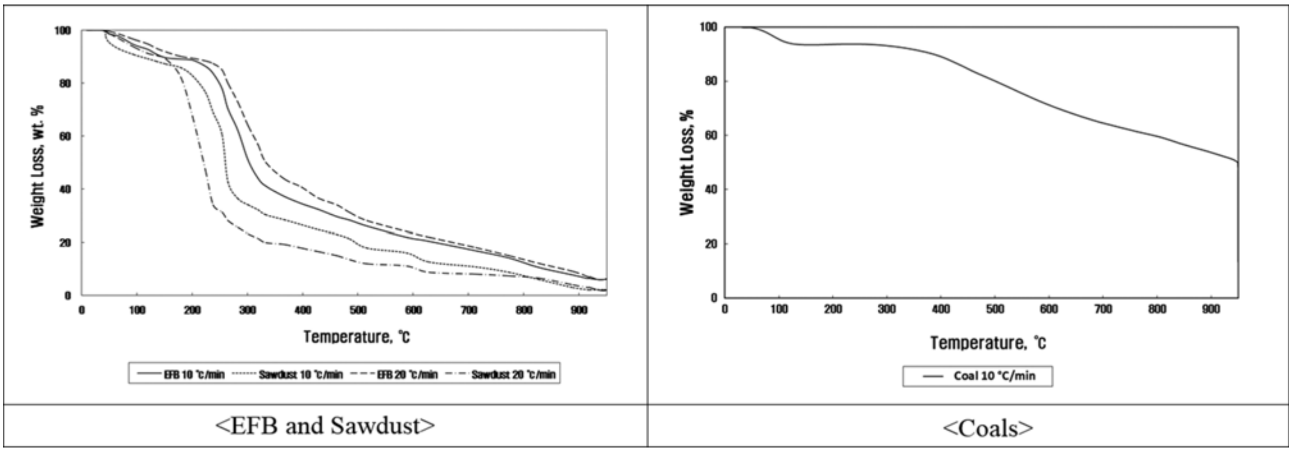
Table 4. Results of elemental analysis for various biomass types and coal

	Elemental analysis [wt%]					HHV [kcal/kg]
	C	H	O	N	S	
EFB	41.81	5.73	37.36	0.84	ND*	3,930
JSC	50.52	6.15	39.41	2.32	ND*	4,952
Palm shell	44.6	6.50	40.20	2.92	<0.1	4,406
Sawdust	45.93	6.65	46.00	0.68	0.16	4,196
Soy bean	43.16	6.9	44.76	0.95	0.20	4,038
Corn straw	42.69	6.16	42.69	0.99	0.21	3,962
Coal	64.7	4.4	11.0	1.2	0.6	6650.1

*ND: not detected

Table 5. Results of proximate analysis for various biomass and coal

	Proximate analysis [wt%]			
	Moisture	Volatile	Fixed-carbon	Ash
EFB	9.63	64.95	19.48	5.94
JSC	2.65	79.80	14.13	3.42
Palm shell	5.92	71.31	17.81	4.96
Sawdust	6.27	78.11	15.04	0.58
Soy bean	9.34	68.95	15.62	6.08
Corn straw	9.31	62.74	14.83	13.12
Coal	5.52	33.55	48.22	12.71



<EFB and Sawdust>

<Coals>

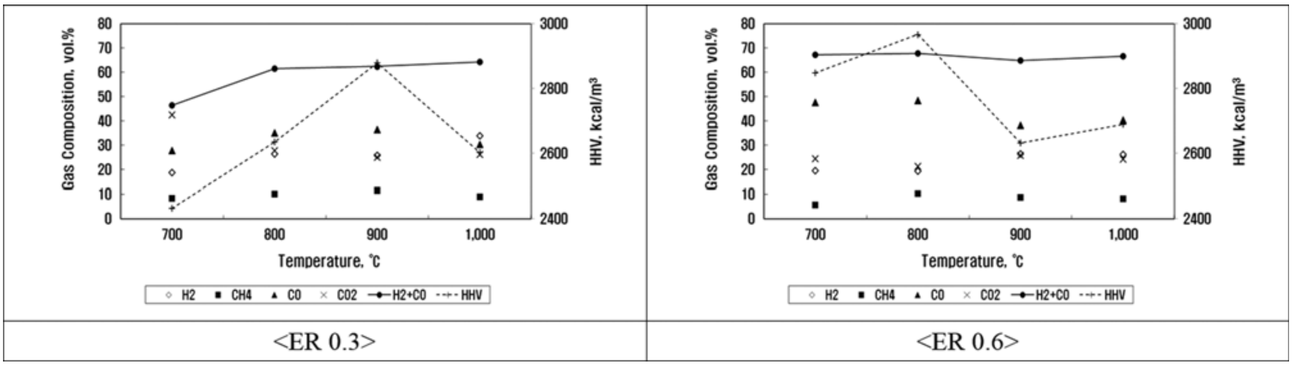
Fig. 2. Fuel TGA results.

be monitored because the main purpose of the procedure is to condense the produced hydrocarbon vapor by thermal cracking. When the biomass is fed into the reactor, it can easily be cracked by thermal heating at high temperature or with a long residence time [21]. The gasification reaction uses all of the combustible gases, excluding moisture and ash, to generate hydrogen and carbon monoxide by oxidation. It was concluded that this process requires a temperature higher than 900 °C [22]. However, the EFB TG graph indicated that the reaction rate of this process was lower than that of sawdust. Although the appropriate temperatures differed, the TG graphs for those samples showed similar trends [7]. Meanwhile, the thermal reaction rate of coal was lower than that of EFB or sawdust. The weight reduction in the TG graph had not completed at 950 °C; thus, coal gasification could be conducted at a higher temperature than EFB.

2. Gasification of Empty Fruit Bunches

The results of EFB gasification showed that the level of hydrogen and carbon monoxide increased with increasing temperature and ER, whereas carbon dioxide levels decreased. These results suggested that thermal cracking increased with increasing temperature, because the endothermic reaction was dominated by a water gas shift (WGS) reaction, which increased the steam gasification reaction by the moisture inside the EFB. However, as the amount of oxygen increased, the exothermic reaction by oxidation dominated and the heat of the reaction increased carbon monoxide [20]. Methane was generated at a component ratio of approximately 10 wt% without a clear correlation with the gasification temperature and ER. Considering the component ratio of syngas, the optimum conditions were a gasification temperature of 800 °C and ER of 0.6. However, in this study, the optimum conditions for producing syngas were a temperature ranging from 900 to 1,000 °C, which yielded the highest amount of syngas and lowest amount of solid residue. During the operation of a power plant that uses gasification, the amounts of syngas and solid residue produced were important factors that affect the power generation efficiency and continuous operation. The HHV of the produced syngas was also estimated, and the results varied with temperature. Additionally, during EFB gasification, there were no high-calorie hydrocarbon compounds. The HHV trend was similar to those of carbon monoxide and methane. It was also affected by carbon dioxide content. Based on these results, it would not be economical to transport syngas over long distances, because its calorific value is low. Eventually, it could be directly used as a gas fuel in the area it is produced.

The carbon conversion rate and cold gas efficiency are important factors for evaluating gasification efficiency. The carbon conversion rate evaluates how many carbon compounds are converted into hydrocarbon gases, which is directly related to the cold gas efficiency [24,25]. Thus, the carbon conversion rate could be calcu-



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<ER 0.6>

Fig. 3. Gas composition from gasification of EFB at different temperatures.

Table 6. Equations of carbon conversion and cold-gas efficiency

Carbon conversion (%)	$12\times D.G.\times(CO+CO_2+CH_4+2\times C_2H_6+3\times C_3H_8)\div(22.4\times C)$
Cold-gas efficiency (%)	HHV of product gas (kcal/kg)÷HHV of feedstock (kcal/kg)×100

*D.G. (Dry Gas)=Product gas flow rate (Nm^3/hr)÷Input feedstock mass rate (kg/hr)

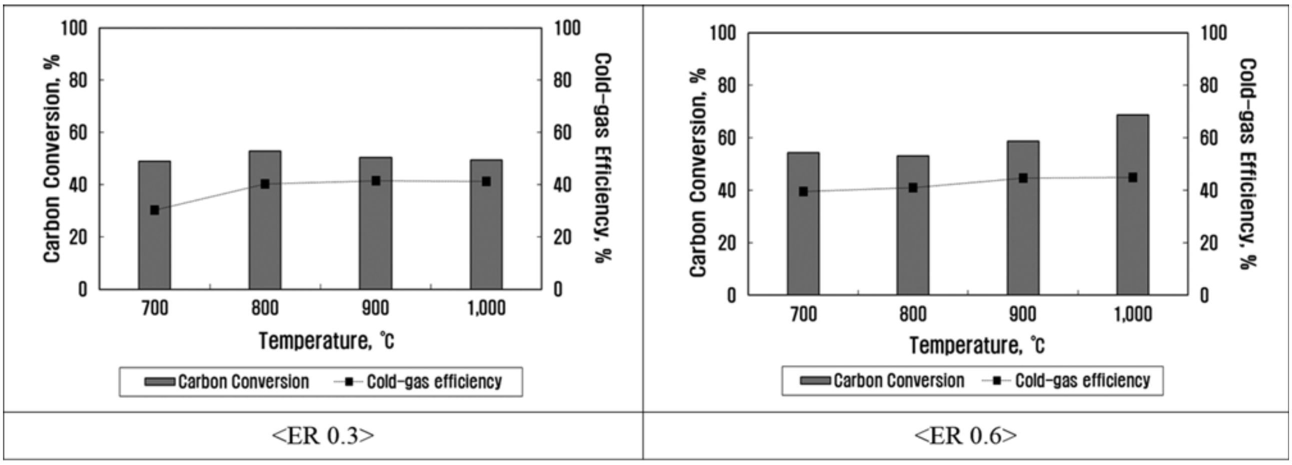

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Fig. 4. Results of carbon conversion and cold-gas efficiency at varying temperatures during EFB gasification.

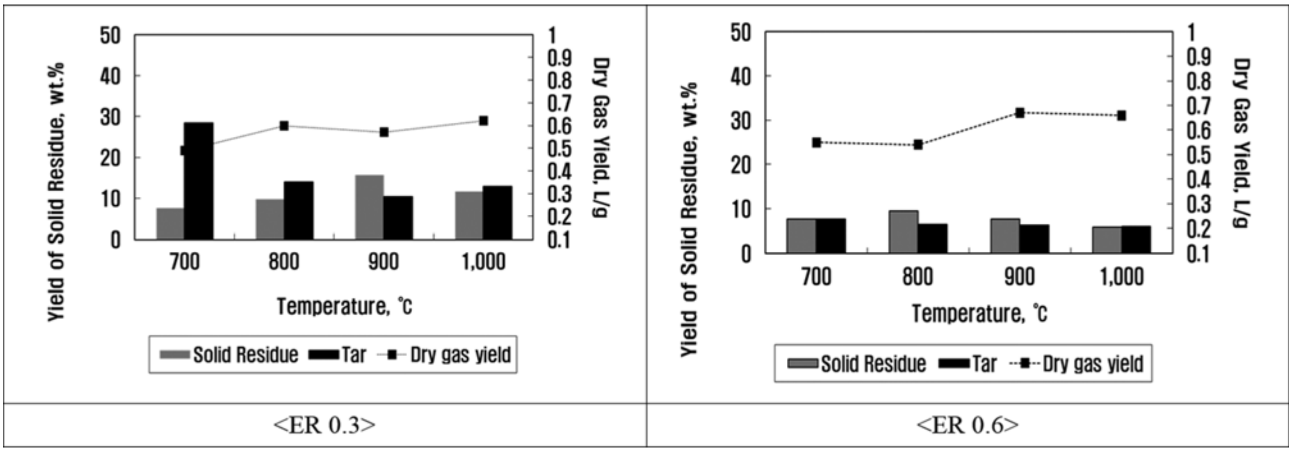

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Fig. 5. Yields of solid residue and dry gas at different temperatures with tar formation in EFB gasification.

lated by the hydrocarbon gases produced from EFB, which originated from the total carbon content of EFB. The relevant equations are presented in Table 6.

We did not consider nitrogen, due to the "N_2 free basis" theory [25]. Fig. 4 shows the carbon conversion rate and the cold-gas efficiency of EFB gasification at different temperature. The carbon conversion rate was the highest at 1,000 °C and ER of 0.6, and the dry gas yield was also highest under those conditions. The cold gas efficiency is correlated with the amount of hydrogen and carbon monoxide. As the levels of hydrocarbon gas increased, the cold gas efficiency increased. Finally, the hydrogen and carbon monoxide increased with increasing ER. Thus, the cold gas efficiency was highest at 900 to 1,000 °C and ER of 0.6.

Fig. 5 shows the yields of solid residue and dry gas with tar formation from EFB gasification at different temperatures. As mentioned, during EFB gasification, tar content decreases with increasing temperature. It was concluded that the conversion ratio from high to low molecular weight compounds increased with temperature because the cracking of those compounds was more intense under high temperatures. Additionally, comparing the experimental results with the result of proximate analysis, the EFB reaction performed well provided that the amounts of ash and char were kept within 10 wt%, constituting the solid residue. However, there was a high amount of tar at 700 °C because organic compounds in EFB were volatized at this temperature and significantly condensed during the oil phase in the scrubber. Although the value of dry gas produced by EFB gasification was below 0.7, it was higher than that from coal gasification. As shown in Fig. 5, the dry gas yield from EFB gasification was affected by changes in temperature and ER. Generally, the syngas yield increased by the same amount as gas production from gasification [24,25]. During EFB gasification, the dry gas yield and ER were optimized at a temperature of 900 °C and ER of 0.6. According to the experimental results, the optimal conditions for continuous operation of EFB gasification are a temperature of 900 °C and ER of 0.6.

3. Co-gasification of EFB with Coal

The co-gasification experiment was conducted with coal at the optimum temperature determined from the results of EFB gasification. The same process and experimental conditions were used. As can be seen in the TG graphs, the co-gasification experiments of EFB with coal were conducted from 800 to 1,000 °C. The EFB gasification results showed that cold gas efficiency 35% and dry gas production exceeded 0.6 L/g. From those results, the appropriate temperature for the co-gasification of EFB with coal ranged from 900 to 1,000 °C. Moreover, the generation of hydrogen increased with temperature; thus, it was concluded that the steam gasification reaction would be more intense with increased moisture content in EFB within that temperature range. Fig. 6 shows the composition of gas from co-gasification at different temperatures and ER. As shown, the syngas yield at 1,000 °C was more stable than that at 900 °C, and the calorific content of syngas also increased with increased coal content. Moreover, more hydrogen was produced from the co-gasification of EFB with coal than from general biomass gasification at 1,000 °C, as predicted by the results of TG analysis due to simultaneous steam gasification. Moisture in the EFB played a key role in this steam gasification, during which hydrogen production increased with increasing temperature, which was also observed for EFB gasification. In addition, sample EFB was fed into the BFB reactor as in-bed feed in this study. This process could have a suitable residence time for the reaction between the moisture in EFB with coal. Additionally, due to the high volatility of coal, hydrogen content increased with increasing coal content. As shown by the weight reduction trend, which was plotted during the TG analysis of coal, the volatile component of coal easily cracked into hydrogen. In addition, the HHV of syngas increased with increasing coal content. Provided that there was more fixed carbon in coal than in EFB, carbon compounds in the coal were not completely converted into low molecular weight compounds during the gasification process. Prior to gasification, initial pyrolysis of coal was conducted at the beginning of the reaction. After the pyrolytic reaction completed, HHV was affected by gas composition provided that highly calorific gases, such as ethane and propane, were produced during coal gasification [8,25]. As a results, the HHV of syngas from coal gasification ranged from 2,249 to 3,441 kcal/m^3, which was higher than that from EFB gasification under the same conditions.

Fig. 7 presents the carbon conversion and cold-gas efficiency of co-gasification. The carbon conversion rate from the co-gasification of EFB with coal decreased with increasing coal content. In addition, cold-gas efficiency decreased as coal content increased. It was considered that the temperature and ER conditions from the co-gasification of EFB with coal should differ from that of EFB gasification, and the initial pyrolytic reaction of coal would produce those results with increasing coal mixing rate [19].

Fig. 8 shows the yields of solid residue and dry gas from co-gasification. The syngas yield from co-gasification of EFB with coal was lower than that from EFB alone. It was concluded that the co-gasification of EFB with coal was less efficient than that of EFB gasification alone. Similarly, the amount of gas produced from co-gasification of EFB with coal increased as ER increased. Regarding the results of EFB and coal co-gasification, a coal content of 20 wt% was determined to be the maximum mixture ratio from

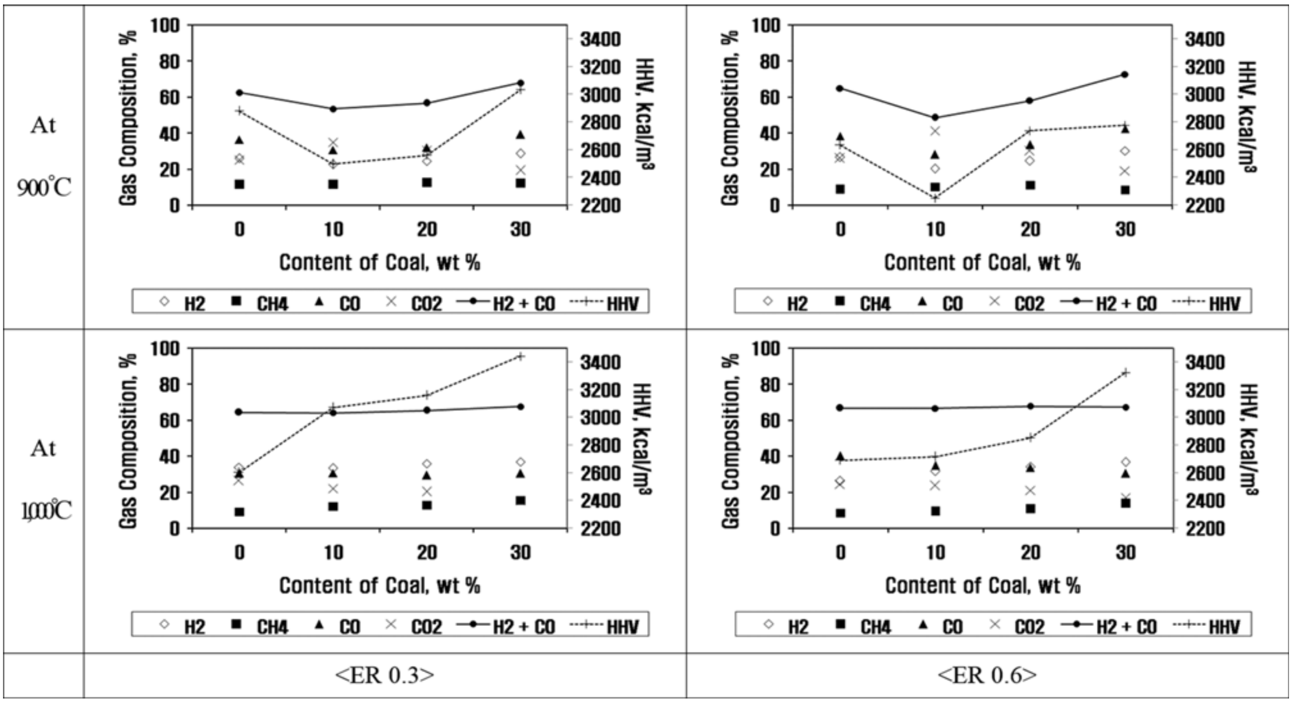

Fig. 6. Gas compositions from co-gasification at different temperatures and ERs.

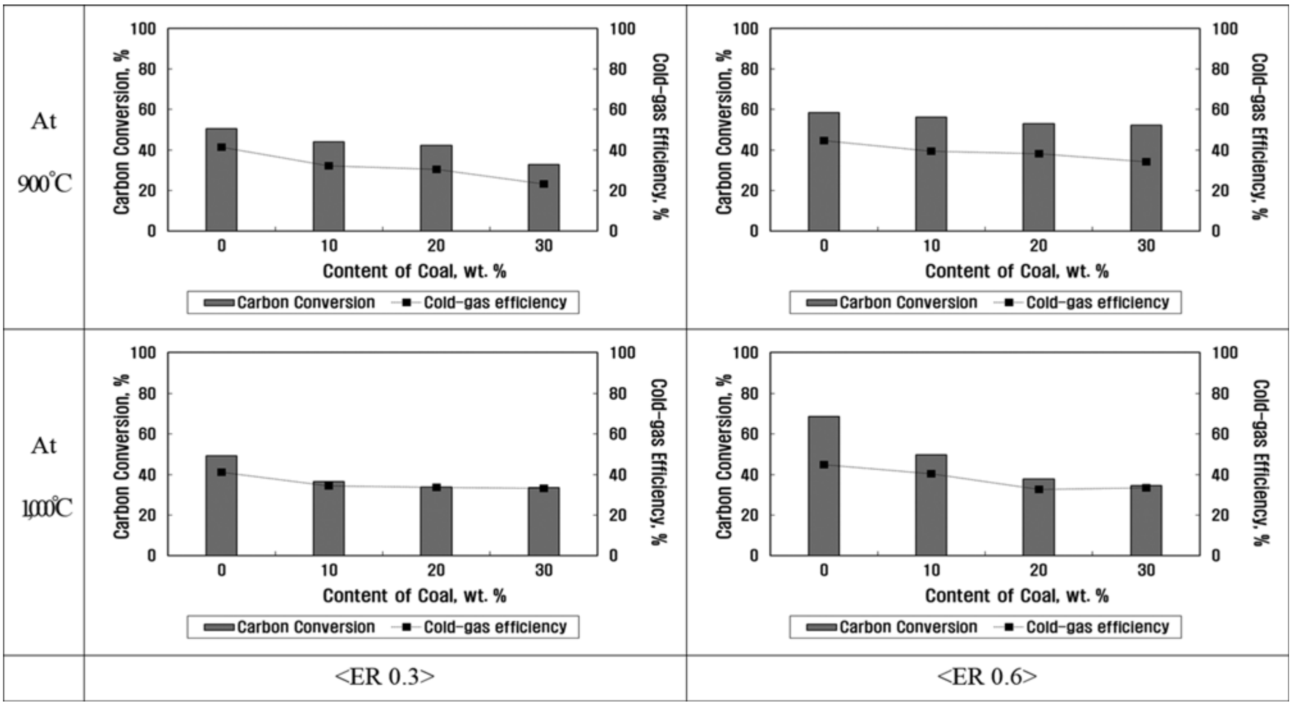

Fig. 7. Results of carbon conversion and cold-gas efficiency in co-gasification.

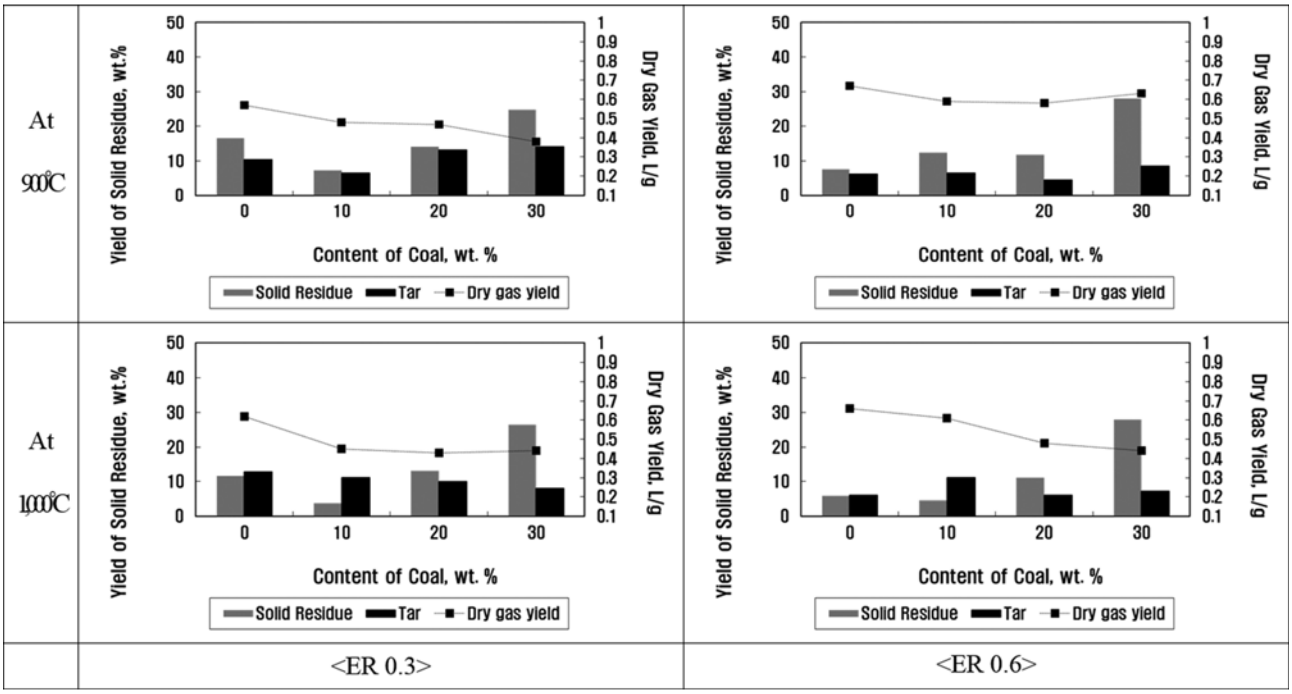

Fig. 8. Yields of solid residue and dry gas from co-gasification.

ER analysis, dry gas yield, and mass balance. When the coal content exceeded 30 wt%, the amount of char was so high that the gasification reaction could continue over a long period. At higher temperature and ERs, the syngas yield increased; however, considering economic factors and the failure of operation due to char production, it was concluded that a coal content of 20 wt% was the most appropriate mixture ratio for continuous operation and stable syngas production at 1,000 °C and 0.6 ER.

CONCLUSION

Experimental tests for physio-chemical and thermal characteristics were conducted to evaluate the applicability of EFB gasification as a byproduct from palm milling. EFB and coal co-gasification tests were conducted to evaluate this process as an alternative solution due to the instability of EFB supply. The results of the gasification experiments demonstrated the efficiency and possibility of syngas production. The following conclusions could be drawn from this work:

1. The EFB was composed of 41.81 wt% carbon, 5.73 wt% hydrogen, 0.84 wt% nitrogen, and 37.36 wt% oxygen. These elemental analysis results were similar to those of sawdust. EFB contained higher moisture content than sawdust at 9.63 wt%. The coal tested in this study contained 66.79 wt%, 4.99 wt%, 2.48 wt%, and 12.13 wt% of carbon, hydrogen, nitrogen, and oxygen, respectively; however, the coal contained 0.24 wt% of sulfur that could be converted into H_2S during gasification.

2. According to TG graph analysis, the TG graphs of EFB and sawdust showed similar trends. The thermal reaction rate of coal was lower than that of EFB or sawdust. As determined from the results of the TG graphs, the EFB gasification experiments were conducted from 700 to 1,000 °C.

3. During EFB gasification, hydrogen and carbon monoxide levels increased with increasing ER. Thus, the cold gas efficiency was highest at a range of 900 to 1,000 °C and ER of 0.6. In addition, the dry gas yield and ER were optimized at 900 °C and ER of 0.6, respectively. According to these results, the optimal conditions for EFB gasification were 900 °C and ER of 0.6 for continuous operation of EFB gasification.

4. From the results of co-gasification of EFB with coal, the optimum mixture proportion of coal content was determined to be 20 wt% by analysis of ER, dry gas yield, and mass balance. For coal content exceeding 30 wt%, the amount of char was so high that the gasification reaction could not operate over a long period.

5. Although higher temperatures and ERs produced better syngas yield, taking economic factors into consideration, including the operation failure by char production, it was concluded that a coal proportion of 20 wt% was the most appropriate for continuous operation and stable syngas production at 1,000 °C and 0.6 ER.

ACKNOWLEDGEMENTS

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