The Potential of High Moisture Biomass for Energy Production Using Plasma – Assisted Gasification

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ABSTRACT

Gasification of biomass has been widely used for energy production. However, biomass feedstock must be low in moisture (< 20 % w.b.), inevitably requiring drying process which is both energy and time consuming. This paper shows the potential of high-moisture biomass gasifying using plasma arc as an external heat supply. It was found that high-moisture biomass can be used as feedstock in the plasma-assisted gasification process. The plasma arc maintained gasifier temperature high enough for reactions involved. The efficiency of the plasma-assisted gasification system operated with high-moisture biomass was more or less the same with that of conventional gasification operated with low-moisture biomass. When the drying energy was taken into account, the efficiency of the plasma gasification system is 15% higher than that of conventional gasification system. Overall, the plasma-assisted gasification system can be operated with high-moisture biomass efficiently and reduces the processes and energy for biomass preparation.

Keywords: plasma-assisted gasification; fixed-bed downdraft gasifier; energy production; high-moisture biomass.

INTRODUCTION

Currently, many countries are paying increasing attention to develop renewable energy resources. However, they are still not able to completely replace fossil fuels due to technological, environmental and social problems. In Thailand, Alternative Energy Development Plan (AEDP) has established for promoting renewable energy utilization including different types of renewable energy including solar energy, wind, water, waste, biogas and biomass.[1] As Thailand is an agricultural country, a great deal amount of agricultural residues is left, which could be used as a resource of biomass energy. Furthermore, the use of biomass fuel can also reduce greenhouse gas emissions compared to that of fossil fuels.

Biomass can be converted to energy via either biological or thermochemical processes, the latter include combustion, pyrolysis and gasification. Gasification is attractive because the system is relatively simple, producing a clean-burning fuel with a greater overall conversion efficiency into electric power compared to combustion based technologies.[2] Technically, it is a technology operated a limited oxygen supply at temperature commonly from 750 up to 1,000 °C. The heat transforms solid fuel into syngas, which is combustible, consisting of carbon monoxide, hydrogen and methane.[3] It can be used to produce power in an internal combustion engine to generate electricity, or used as fuel gas in a burner to produce heat.

Gasification process is affected by a number of variables both chemically and physically such as biomass type, size, shape, porosity, bulk density, ash content, etc.[4] Among these, moisture content is one of the most important factor affecting gasification, especially in downdraft gasifiers.[5] Arjharn *et al.,*[2] reported that the 100-kW fixed bed downdraft gasification was difficult to operate continuously if the biomass feedstocks contain moisture content higher than 20% (w.b.). In addition, the higher moisture content of biomass would normally generate high tar content in the syngas because of the drop of gasifier temperature. The larger tar content reduces the heating value and clog-up gas pipelines or engines.[6] Therefore, the use of biomass feedstocks entails several preparation processes, which result in the high cost of production, especially from the drying process. However, uncontrolled biomass quality will reduce the gasification system efficiency as a consequence.

The solution to these problems might be achieved by maintaining the appropriate gasifier temperature during gasification process. Recently, there is a study suggesting that using plasma arc as the supporting heating source for gasification can keep a desired range of temperatures, solving the problem of physical variance in a high-moisture biomass feedstock, since plasma arc can build up temperatures higher than 1,500 °C and increase the reaction rate.[7] Moreover, the heat from plasma arc can compensate the heat losses in the system[8] and reduce an amount of tar in the biomass.[9] Nonetheless, an application of plasma arc technology in a heating process in order to improve gasification system is little found in literatures and most of them were carried out in the laboratory scale.[9,10] Therefore, the researches on plasma-assisted gasification at a pilot scale using a high-moisture feedstock would be an alternative approach of energy production. In the present paper, biomass with varying high moisture levels (16-34% w.b.) was served as raw material to test the plasma-assisted gasification system. The study was carried out by assessing gasifier temperature, produced gas quality and system efficiency.

MATERIALS AND METHODS

Fuel sample

Giant Leucaena (*Leucaena leucocephala* (Lam.) de Wit) stems with 30–40 mm in diameter were selected and cut into 50–60 mm lengths using a circular saw (Figure 1). The moisture content levels used were 16%, 28% and 34% (w.b.) The highest moisture level used is freshly cut wood, while the medium and low ones were obtained after sun drying for a different periods of time. Proximate analysis, such as moisture content, ash, volatile matter and fixed carbon, followed the standard of ASTM D1762-84, and the heating values was determined using a bomb calorimeter as per ASTM D2015-77 standard. Ultimate analysis was carried out for the amount of carbon, hydrogen, nitrogen and sulfur using CHNS-932 EDXRF analyzer. The oxygen content was calculated by means of the element difference.[2]

Experimental equipment

A direct current (DC) plasma torch obtained from High Temperature Technologies Corp., Chateauguay, QC, Canada, was used to provide additional heat for the study of high-moisture feedstock gasification. The setup included a 50-kW plasma torch, high voltage oscillator, high voltage power supply system, and water supply system. Electricity was transformed into the thermal plasma arc through electrodes made from tungsten (cathode) and copper (anode). The operational voltage and current of the torch were 300 V and 120 A, respectively. Compressed air with a relative pressure of 700 kPa, which is used as the plasma-forming gas, was injected between these 2 electrodes to establish the arc. The intense heat generated on the 2 electrodes was cooled down using cold water

from the water supply system that was maintained at 10 °C. The temperature of the water leaving the plasma torch was controlled at < 50 °C to avoid the damage of rubber seals. The simplified schematic of the plasma arc torch and its specifications are shown in Figure 2 and Table 1, respectively.

The gasifier is based on a fixed bed downdraft gasifier which was collaboratively designed and developed by the Suranaree University of Technology, Thailand and Satake Corporation Co., Ltd., Japan. The gasifier was manufactured from mild steel and equipped with an inner lining of insulation and high temperature ceramic. The gasifier height and inner diameter were 3.11 m and 0.75 m, respectively. The plasma torch was installed in the combustion zone, approximately 2.28 m from the top of the reactor. A screw conveyor with a water jacket was installed for charcoal removal. Nine air nozzles with a diameter of 10 cm were installed around the combustion zone. The gas cleaning and cooling system was located next to the gasifier, including a cyclone collector, water scrubber, chilled water scrubber, and bag filters. The various elements of

Fig. 1: Leucaena timber as biomass fuel

the downdraft gasification power plant are shown in Figure 3 and the plasma gasification process is shown in Figure 4.

Experimental method

Giant leucaena fuel was delivered to the reactor with an electric hoist. Workers manually filled the fuel until it reached the predetermined level. All valves at the air tube were opened in order to let the air flow into the reactor. Then the scrubber was turned on to run the system, and the fuel was lighted with a plasma torch at the combustion zone. The heat generated in this zone would evaporate from fuel in the drying zone and cause gasification. After gasification was complete, syngas would come out of the reactor and flow to the gas cleaning and cooling system. Contaminants composed mainly of tar and dust in the syngas were eliminated by the cyclone, followed by the water scrubber and chilled water scrubber. As tar is condensed at low temperatures, large amounts of tar will be eliminated at the chilled water scrubber. Finally, bag filters, which can entrap particulate matters as small as 0.1 mm, were used for the final stage prior to the syngas passing to the flare station. The syngas flow rate was held at the best performance of the blower at 220 $(Nm)^3$ h^{-1}. The flow rate was monitor using an electronic flow meter (Model DIG-SIDO-O, Nippon Flow Cell Co., Ltd, Tokyo, Japan) which was installed between the bag filters and gas flare. Each test was operated for four hours. The amount of biomass to refill the reactor to the predetermined level, with respect to time, was used to calculate the feedstock consumption rate. The ash discharge was controlled to be the same at 5% for all the experiments.

For the temperature distribution inside the reactor, 6 K-type thermocouples were installed
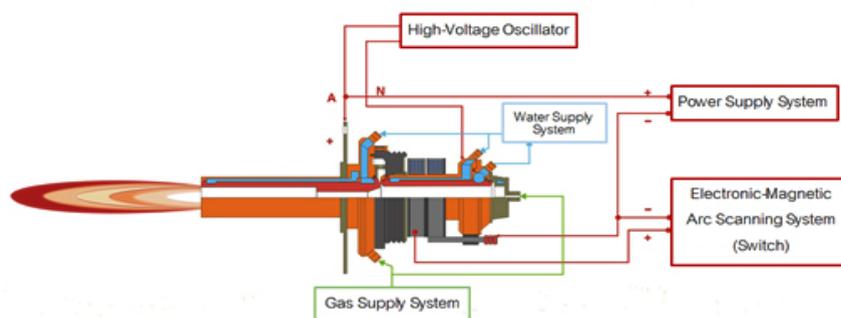
Fig. 2: Schematic of the plasma arc torch

vertically at 0.66, 1.06, 1.46, 1.86, 2.28 and 2.70 m downwards from the top of the gasifier. The protrusion of the thermocouples from the gasifier wall was 10 cm. The temperatures were measured at intervals of 5 min to record the thermochemical conversion phases: drying, pyrolysis, combustion, and reduction.[2, 11]

The composition of the syngas was analyzed using an online infrared gas analyzer (Model Gasboard-3100, Wuhan Cubic Optoelectronics Co., Ltd., Wuhan, China) located at between the bag filters and the flare station. Tar and dust contents were measured by drawing the gas using a vacuum pump. The moisture content in the syngas was measured by $CaCl_2$ contained in a U-shaped tube, which was submerged in ice. Then, approximately 300 L of syngas was drawn through a paper filter (GF/B) with a 47 mm diameter. The total tar and dust contents were quantified by drying the paper filter in an oven at 105°C for about 6 hours.[12] The dried filter then was rinsed with anisole to wash away tar from the filter. The difference in weight of the filter after drying was used to calculate the individual tar and dust contents with respect to the dry gas volume. The data on the syngas composition and the tar and dust contents was collected every 5 min. and 30 min. respectively.

The performance of the gasification system was evaluated by the following equation:[13]

$$\eta_{cg} = (V_g * LHV_g) / (m_{fuel} * LHV_{fuel}) + P_{torch} \qquad ...(1)$$

η_{cg} = the cold-gas efficiency (%)

Table 1: Specification of the plasma arc torch. (Model : Gas Plasma Arc Torch AK-1-50 DC)

Parameter	Value
Power	50 kW
Voltage (max)	300 V
Current (max)	250 A
Air	2.8 g s^{-1}
Water (max)	500 g s^{-1}
Life time of electrodes	200 h
Efficiency	65 %
Diameter of nozzle	25 mm
Sizes	30 × 60 mm
Weight	10 kg

m_{fuel} = the waste reject consumption rate (kg h^{-1})

LHV_g = the calorific value of the gas produced (MJ (Nm)$^{-3}$)

LHV_{fuel} = the low heating value of the rejected waste (MJ kg^{-1})

V_g = the volume flow rate of the gas produced (Nm^3 h^{-1})

P_{torch} = the power input for the plasma torch (MJ h^{-1})

RESULTS AND DISCUSSION

Biomass fuel characteristics

Table 2 shows characteristics of biomass raw material at different moisture content. The increase in moisture content causes an increase in bulk density but decrease the calorific value. It implies that less energy is generated during the biomass decomposition because partial heat is lost for moisture evaporation during gasification process. In other words, the gasifier temperature will drop when feedstock has high moisture content, resulting in incompletely pyrolysis process during gasification.[14] Susastriawan *et al.,*[5] reported that feedstock with moisture content higher than 30% produces low quality syngas gas, thus low gasification efficiency. Eventually, the downstream applications (turbine, engine and gas burner) cannot operate efficiently. Normally, to cope with the high-moisture biomass material, the drying process is inevitably needed. However, this process is time consuming and requires a great amount of energy.

For the proximate values of *Giant Leucaena* consisting of volatile matter, fixed carbon and ash contents are 80.94%, 17.53% and 1.53%, respectively. These values are in the range of biomass materials in Thailand as reported by Arjharn et al.,[2] that studied electricity production from different biomass feedstocks (10 types of feedstock) using a pilot-scale downdraft gasifier. The ultimate analysis indicated that elemental-basis carbon and hydrogen proportions of the *Giant Leucaena* (Table 2), principal elements contributing to syngas production during thermochemical reactions, were fairly high and suitable for use in gasification process. The proportion of nitrogen and sulfur was found with

a small value (< 1%), which is consistent with the study reported by Quaak *et al.,* [15]

Temperature profile

Gasifier temperature is a crucial parameter for syngas production. The thermochemical reactions cannot take place efficiently if the temperature is too low. An increase in feedstock moisture content will inevitably cause the drop in gasifier temperature. Biomass with more than 30% moisture content reduces calorific value of syngas.[14] The effect of different moisture levels (16, 28 and 34% w.b.) on temperature profile when using plasma arc as an additional heat to deal with high-moisture biomass is shown in Figure 5. It was found that the gasification system was able to operate regularly and continuously although the moisture content was over 30% w.b. At the lowest level of moisture content (16% w.b.), the temperature slightly increased between the 0.66 and 1.06 m positions with an average of 80 $^{\circ}$C. The drying process took place in this zone. The moisture in the feedstock is evaporated until the temperature increases up to 200 $^{\circ}$C.[11] Subsequently, the temperature increase rapidly between the 1.06 and 2.28 m positions (~ 900 $^{\circ}$C), where the plasma arc and air were supplied to the gasifier. The pyrolysis takes place at temperature between 200 and 700 $^{\circ}$C,[5] leave releasing volatile consisting mainly of CO and tar and leaving tar behind. At temperature of between 800 and 900 °C, the combustion occurred, transferring heat to promote reactions in other zones. At the last stage (between 2.28 and 2.70 m), the temperature

drop slightly to ~ 800 $^{\circ}$C because of endothermic reactions by which the product gases produced from the upper zone are reduced with carbon (charcoal), producing syngas consisting mainly of CO and H_2.[11]

Not surprisingly, the overall temperature profile of the higher levels of moisture content (28 and 34% w.b.) is lower than that of 16% w.b. because of heat loss during moisture evaporation. The temperature kept stable at ~ 40-45 $^{\circ}$C until the position of 1.48 m and then increased greatly between 1.48 and 2.28 m positions. The highest temperatures of 28% and 34% w.b. were found at the position of plasma torch installed, which were 850 and 800 $^{\circ}$C, respectively. Although the temperature of higher moisture feedstock increased much slower, the temperature in the combustion zone was still high enough to generate heat for the adjacent zones. The temperature at the final stage (reduction zone) was approximately the same for all moisture levels of biomass.

Moisture content of the feedstock plays a very important role in the gasification process. The upper limit of the moisture content for downdraft gasification is usually no more than 20 % w.b.[16] to keep the system operated efficiently. In fact, the use of a feedstock with high moisture content in this study is almost impossible because considerable heat is used to evaporate moisture from the feedstock itself, reducing the overall gasifier temperature. Consequently, the heat available is not sufficient

Table 2: Characteristics of the biomass fuel

Analysis	Parameter	Value		
Physical Properties	Moisture Contents (%w.b.)	16.02	28.12	34.28
	Density (kg/m³)	335.95	391.94	427.57
	Size (mm)	L = 50 – 70 mm, Ø = 25 – 60 mm		
Calorific Value(MJ/kg)	Higher Heating Value	16.02	13.73	12.59
	Lower Heating Value	14.54	12.12	10.92
Proximate Analysis(wt%, d.b.)	Volatile Matter	80.94		
	Fixed Carbon	17.53		
	Ash	1.53		
Ultimate Analysis(wt%, d.b.)	Carbon	49.20		
	Hydrogen	6.05		
	Nitrogen	0.47		
	Sulphur	0.03		
	Oxygen	42.74		

to drive other gasification reactions. Similar finding was found by Sulaiman *et al.,*[17] who revealed that gasifying oil-palm fronds with moisture over 20% w.b. in a traditional downdraft gasification system caused a considerable drop in gasifier temperature (~ 600 °C) and resulted in extinguishing the flame at the flare. However, an additional supply of external heat using a plasma arc in this study can reduce the limit of the gasification process when using a feedstock with a high moisture content.

Characteristics of syngas

In this experiment, the syngas flow rate and ash discharge rate were controlled at the same levels for all the moisture content levels, and were 220 $(Nm)^3$ h^{-1} and 5 wt%, respectively. It was found that the increase of the moisture content resulted in an increase in the feedstock consumption rate (Table 3). Across all moisture treatment conditions, the equivalence ratio, which is the ratio of the actual A:F ratio to the stoichiometric A:F ratio, is found to

NO	Item name	NO	Item name
1	Plasma torch	5	Water scrubber and bag filter
2	Downdraft gasifier	6	Gasifier and plasma control Unit
3	Ash discharge screw	7	Gas flow meter and gas sampling
4	Cyclone collector	8	Flare station
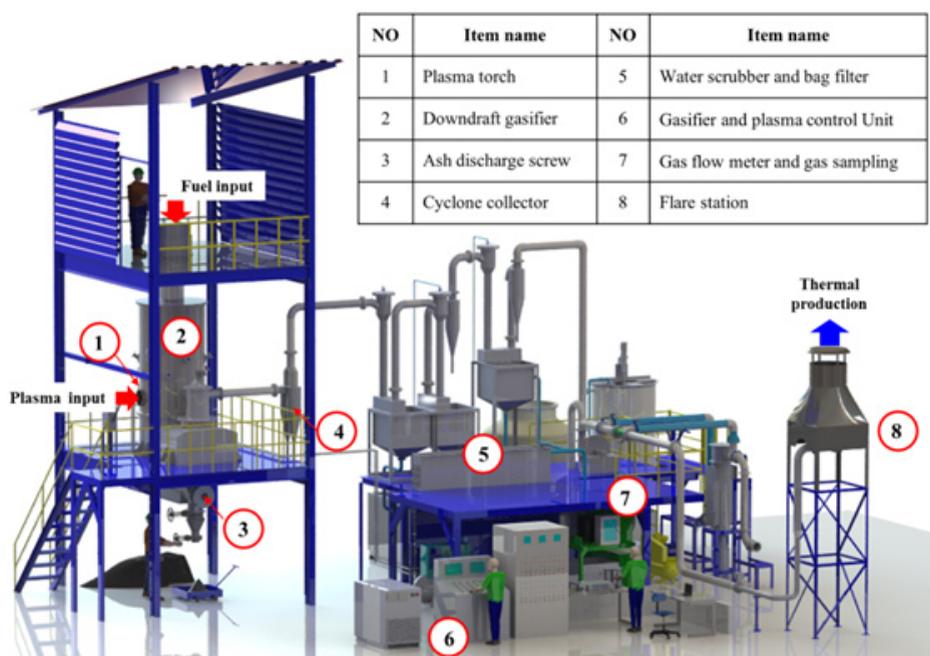
Fig. 3: Plasma-assisted gasification system
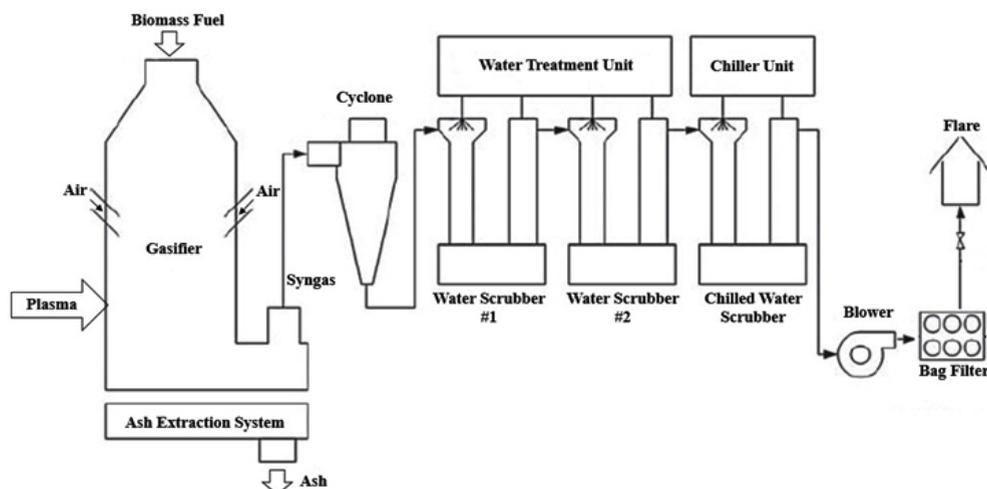
Fig. 4: Schematic view of a pilot-scale downdraft biomass gasification

be almost similar with an average value of 0.26. This result allows for the comparison of the effect of the moisture content on syngas quality and gasification efficiency.

The syngas composition of gasified biomass at different moisture levels is shown in Table 3. It found that the syngas quality was substantially influenced by the moisture in biomass. The CO decreased ~ 28% when the moisture content increased from 16 to 34% w.b. The decrease in the CO concentration with an elevated moisture content may be attributed to the increase in the feedstock density which creates a pressure drop along the gasifier, causing less O_2 to be available. When the O_2 decreases, the CO decreases accordingly.[7] On the contrary, the H_2 was found to increase with an increase in moisture content of the biomass. This was expected because more water is available for the H_2 producing reactions. Compared with the feedstock moisture content of 16% w.b., the concentration of H_2 increased by 11.9% and 17.4% when the moisture of feedstock increased to 28 and 34% w.b., respectively. The increased H_2 and decreased CO

with respect to the moisture content of the feedstock is consistent with the experiments of Zainal *et al.,*[18] and Sharma.[19]

Considering the calorific value (LHV) of the syngas, it reduced slightly when the moisture content of feedstock increased. Although the calorific value decreased with the increased in moisture content, it was still high enough for use as fuel for a gas engine, which requires a minimum energy of approximately 4.2 MJ $(Nm)^{-3}$.[15] The difference between the low and high moisture contents in the calorific value may be mainly attributed to the variation of the temperatures available for reactions in the gasifier. It can be explained by the fact that the high temperature from plasma causes large amounts of radicals, electrons, ions, and excited molecules, thus increasing the rate of reactions and producing more quality syngas.[13] However, this phenomenon is demolished by an elevated moisture content.

System performance evaluation
The performance of the plasma-assisted gasification for the *Giant Leucaena* fuel at varying

Table 3: Experimental results of the plasma-assisted gasification test

Parameter	Unit	Moisture content of feedstock (%wt., w.b.)		
		16	28	34
Syngas flow rate	Nm³/h	216.40	215.50	218.00
Equivalent ratio	-	0.25	0.25	0.28
LHV of fuel	MJ/kg	14.54	12.12	10.92
Feedstock consumption rate	kg/h	109.90	132.35	129.60
Ash discharge rate	kg/h	5.52	5.53	5.51
	%	5.02	4.17	4.25
Composition	dry basis			
CO	%	19.34	14.51	13.84
H_2	%	20.30	22.71	23.83
CH_4	%	3.30	2.37	2.08
O_2	%	0.61	0.48	0.63
CO_2	%	13.03	15.10	14.80
LHV	MJ/Nm³	5.80	5.12	5.05
Syngas yield	Nm³/kg	1.97	1.63	1.68
Energy yield	MJ/kg	11.42	8.34	8.49
Energy input (Fuel)	MJ/h	1,597.95	1,604.08	1,415.23
Energy input (Plasma Power)	MJ/h	129.60	129.60	129.60
Energy output (Syngas Energy)	MJ/h	1,255.12	1,103.36	1,100.90
Cold-gas efficiency (η_{cg})	%	72.66	63.63	71.34
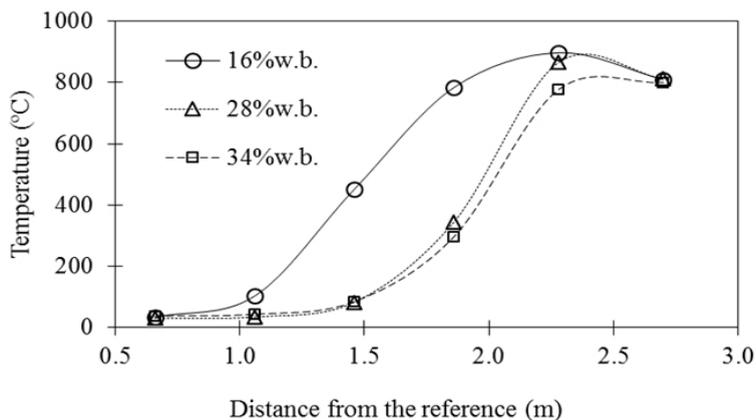
Fig. 5: Temperature profiles of the biomass fuel along the gasifier at different moisture content levels

Table 4: Tar and dust contents with respect to feedstock moisture content

Moisture Content (%wt., w.b.)	Impurity (mg/Nm³)		
	Tar	**Dust**	**Total**
16	3.11	85.27	88.38
28	2.97	62.56	65.53
34	3.32	68.88	72.20

moisture contents is presented in Table 3. For each run, the plasma energy input was maintained at ~130 MJ h^{-1} or ~76% of maximum capacity. The syngas yield was found to decrease with the increased moisture content with approximately 15% reduction. The decrease in the syngas yield is ascribed to the increase in the feedstock consumption rate from 109.90 to 129.60 kg h^{-1}. The energy yield, which was calculated as the ratio of syngas energy to its corresponding consumption mass, also showed a similar trend. It reduced considerably by 27% for the same range of moisture content.

The cold gas efficiency (η_{cg}) is used to determine the energy efficiency of a gasification process. It was found that when the moisture content of feedstock increased from 16 to 28% w.b., the η_{cg} reduced by 9.03%. This is expected because partial heat is used to evaporate moisture, thus less heat is available for promoting endothermic gasification. However, the η_{cg} increased when the moisture content of feedstock increased from 28% to 34% w.b., which is close to that at 16% w.b. (~ 71.34%). This

is due to the heating value of feedstock at 34% w.b., which was less than that of lower moisture content.

In general, drying process must be considered for high-moisture biomass prior to its use in a conventional gasification system. For *Giant Leucaena*, Arjharn[20] found that the drying process using a rotary dryer required specific energy consumption (SEC) of 13.89 MJ (kg$_{evaporated\ water}$)$^{-1}$. If the energy required to reduce moisture content from 34 to 16% w.b. is taken into account, the overall energy efficiency of conventional gasification system is 55.62%. However, at the same initial moisture content of 34% w.b., the overall energy efficiency of gasification system can increase up to 71.34% with an assistance of plasma heat. This confirms that the use of plasma-assisted conventional gasification can reduce steps and energy in the biomass preparation, thus increasing overall system efficiency.

Tar and dust contents

Tar and dust play a crucial role in the gasification process and subsequent applications. They lead to blocking and fouling of downstream applications such as turbines and engines.[21] Table 4 shows the effect of moisture in biomass fuel on tar and dust during plasma-assisted gasification. A variation on tar and dust contents was found with varied moisture content. The tar was found with a low content ranging from 2.97 to 3.32 mg (Nm)$^{-3}$ for the biomass tested. The dust content of the lowest moisture level of 16% w.b. was higher than the others. Normally, the amount of tar and dust from gasification is 50-500 mg (Nm)$^{-3}$.[4] Nonetheless, it depends on

material specifications, working condition design and collecting as well as analysis.[22] Moreover, the performance of removing tar and dust depends on the composition and amount of tar and dust as well as the gas cleaner used.[23] For the experiment, results confirm that plasma-assisted gasifcation system produced syngas that is lower than the maximum limit for an internal combustion engine suggested by Bhattacharya *et al.,*[12] and Quakk *et al.*[15]

CONCLUSIONS

Biomass at varying moisture levels between 16 and 34% w.b. was used to produce syngas using a pilot-scale downdraft gasification power plant with an external heat of plasma arc. The result showed that moisture affected the temperature in the gasifier. When the moisture of the biomass fuel increased, the temperature level in the reactor decreased obviously. However, the temperature in the combustion zone was high enough for gasification process. Furthermore, it affected the gas produced, especially CO and H_2 concentrations in the syngas, causing a variation of calorific value. The tar and dust content is acceptable for the downstream applications (< 88.4 mg $(Nm)^{-3}$). The system performance of plasma-assisted gasification system presented in terms of cold-gas efficiency was found to range between 63.63 and 72.66% at varying moisture contents, which is in the same range of conventional gasification system. Overall, it shows that plasma-assisted gasification can reduce limit of biomass utilization in terms of moisture content. Moreover, it can reduce steps and energy required for preparing biomass feedstock.

ACKNOWLEDGMENTS

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