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AIR GASIFICATION OF PALM BIOMASS FOR PRODUCING TAR-FREE HIGHER HEATING VALUE PRODUCER GAS

ZULKIFLI AB RAHMAN*; N RAVI MENON* and KU HALIM KU HAMID**

ABSTRACT

The use of palm biomass for energy generation has been gaining momentum in recent times on a global level. A tar-free producer gas can be obtained in a properly designed biomass gasification process. In the current study, a tar-free palm biomass gasification system by high-temperature air is proposed. This concept was demonstrated on a pilot scale fixed bed using empty fruit bunches (EFB) under autothermic conditions. The pre-treated EFB were initially pyrolysed, and the resulting char was partially gasified in the gasification zone (oxidation zone) followed by combustion of the char residue at the reduction zone (bottom of gasifier) in an oxidation atmosphere.

As the quality of the producer gas was found to be dependent on the smooth flow of the fuel and the uniformity of the pyrolysis, the difficulties encountered during the experiments are also discussed. The optimum operation of the gasifier ranged between 1.71 and 2.34 Nm^3 kg^{-1} of air-fuel ratios at values of 28.2 and 37.0 kg hr^{-1} of 15% moisture feed rate, which gives a producer gas with a good heating value of about 5.18 MJ Nm^{-3} at a volumetric flow of 92.47-101.78 Nm^3 hr^{-1} producer gas. It was concluded that the pre-treated empty fruit bunches are easy to gasify in a downdraft gasifier to produce good quality gas for process heating and power generation with minimum polluting by-products.

Keywords: empty fruit bunches, gasifier, performance efficiency, tar-free producer gas quality.

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INTRODUCTION

With respect to global issues of sustainable energy and greenhouse gas reduction, biomass is getting increased attention as a potential source of renewable energy. Managing renewable energy using biomass in an effective way is a challenge for the energy industry (Department of Energy, 2000). Biomass used as an energy source can reduce the carbon dioxide (CO_2) greenhouse effect, sulphur dioxide (SO_2) and nitrogen oxides (NO_x) (McKendry, 2002) due to its characteristics of neutral carbon and less sulphur content. The term biomass means any plant-derived organic matter. Biomass can play a substantial role in a more diverse and sustainable energy mix. It can be treated in a number of different ways to produce heat, electricity and gaseous product. In general, such methods are divided into biological and thermal treatments. The biological treatment processes are hydrolysis, fermentation and anaerobic digestion. The thermal treatment processes are combustion, gasification, pyrolysis and liquefaction. Different products are gained from the application of these processes, and different energy and matter recovery systems can be used in these treatment process. Direct combustion provides heat, for example for steam production as well as for power generation. Among all the biomass conversion processes, gasification is one of the most promising. The energy efficiency in the case of gasification is higher than that of combustion.

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* **Malaysian Palm Oil Board, P. O. Box 10620,**
50720 Kuala Lumpur, Malaysia.
E-mail: zar@mpob.gov.my

** **Faculty of Chemical Engineering,**
Universiti Teknologi MARA,
40450 Shah Alam, Selangor, Malaysia.

Four major steps are known to occur during the gasification process. The first step is in the drying zone, during which the biomass descends into the gasifier and the moisture is removed using the heat generated in the zones below by evaporation. The second step is in the pyrolysis zone, where the dried biomass is converted into charcoal and volatile compounds. The third step is in the oxidation zone, where the volatile products of pyrolysis are partially oxidised in highly exothermic reactions. The final step is in the reduction zone where the char is converted into producer gas and leaves the gasifier. One of the major technical issues in biomass gasification is the problem of efficient, reliable and economical removal of tar from the gasification process. The work here will add new findings for application to the technology. Tar is a complex mixture of condensable hydrocarbons, which includes single-ring to 5-ring aromatic compounds along with other oxygen-containing hydrocarbons and complex polycyclic aromatic hydrocarbons (PAHs). Producer gas from biomass gasification contains particulates and organic contaminants (tar), which, if not removed, can cause severe operational problems.

Gasification of biomass is primarily done in fixed beds (updraft/downdraft), circulating/bubbling fluidised beds and indirect gasifiers (Czernik *et al*., 1995; Bridgwater, 2003). The fixed bed gasifiers are suitable for small applications (<10 MWe) while the fluidised bed gasifiers are cost-effective in large-scale applications that generate over 15 MWe (Barker, 1996; Sims, 2003; Yang *et al*., 2006). Fixed bed gasifiers are relatively simpler and reliable; are amenable to gasifying different kinds of feedstocks, offer low particulate concentration in the product gas, and can achieve higher efficiencies than other reactors (Brown *et al*., 1986; Kurkela *et al*., 1993). The complete gasification system consists of a gasification unit (gasifier), purification unit and energy converter-burners or internal combustion engine (Chandrakant, 1997). The key to a successful gasifier design is to understand the properties and thermal behaviour of the biomass that is fed to the gasifier (Yin *et al*., 2002).

Among the available biomass, empty fruit bunches (EFB), produced in abundance from the palm oil mill, can be an important option for the replacement of fossil fuel in electricity generation. Currently, there are about 415 palm oil mills throughout Malaysia with an average capacity at 45 t hr^{-1}, producing more than 19 millions tonnes of palm oil mill biomass (EFB) per annum (equivalent to 12 × 10^4 millions MJ). Thus, there is potential for converting at least 50% of the biomass into producer gas through gasification technology. The conversion of EFB to gaseous fuel provides opportunities for retrofitting the existing biomass boiler, and for displacing natural gas in process heating and power generation. The producer gas produced also plays an important role as an intermediate in the production of several industrial products, such as Fisher-Tropsch liquids, methanol and ammonia. This article presents some performance assessments on an innovative design of a fixed bed palm oil mill biomass gasification system aiming at producing tar-free quality producer gas for downstream applications.

EXPERIMENTAL

Materials

The biomass used in the experiment was palm oil mill biomass, namely EFB from palm oil mill processing. EFB is found in abundance in the palm oil mills of Malaysia. The proximate and ultimate analyses of the EFB were carried out. The proximate analysis (moisture, volatile matter, char and ash) was carried out by using ASTM E872-84 (American Society for Testing and Material) Standards and NREL LAPO05 (National Renewable Energy Laboratory). The average proximate and elemental analysis of EFB is shown in *Table 1*. Air was used as the gasification agent in all the tests.

TABLE 1. THE PROXIMATE AND ELEMENTAL ANALYSIS OF FEEDSTOCK (in dry basis)

	Proximate analysis (wt %)				
EFB	Moisture (%)	Volatile matter (%)	Ash (%)	Fixed carbon (%)	Heating value (kJ kg^{-1})
	0	87.0	4.6	8.4	18 795
	Ultimate analysis (wt %)				
EFB	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)
	45.9	5.7	49.6	0.8	Nil

Note: EFB – empty fruit bunches.

The study was based on an open-core downdraft gasifier, in which both the fuel and the air flow downwards through the reactor enabling the pyrolysis gases to pass through a converging hot bed of char, supported by a grate at the bottom of the gasifier. Tests were performed in a downdraft gasification system at atmospheric pressure, with indirect heating. The system's major components consisted of a downdraft gasifier, biomass feeder, air pre-heater, ash separator, venturi wet scrubber, gas drier and two blowers (0.25 kW, 0.5 kW). Sampling units for gases, tar and particles were installed at the gasifier exit and after the gas purification system before flare-off (*Figure 1*). A flow meter to measure gas flow rate was placed after the gas cooler/scrubber. The valve at the inlet of the gasifier was able to adjust the air flow rate going into the gasifier. The K-type thermocouples were installed at the same height as the four nozzles to measure temperature at this point as the reference temperature of the gasifier.

Methods

The pre-treated EFB (10 kg) was fed into the gasifier and ignited. After ignition, air was supplied with a 0.25 kW blower. At the beginning, gas from the gasifier by-passed downstream units (from the ash separator to the atmosphere) to prevent pollutants from contaminating the units. This start-up operation was continued for 30 min, after which the gas flow rate to the downstream units was roughly constant. The air-flow rate at the gasifier inlet was kept between 8 and 10 m^3 hr^{-1}, a rate that enables quality producer gas production. This steady-state operation was continued for 1 to 2 hr, depending on the flow rate setting, which in turn controlled the fuel consumption rate. An ash port was provided at the side of the bottom of the gasifier to remove the ash collecting there. The EFB residue and char remaining in the gasifier were recovered and weighed after each experiment. The grate was operated at regular intervals to remove ash accumulating on the grate. Sampled producer gases were collected in non-permeable Teflon sampling bags, and analysed by using gas chromatography with TCD and FID detectors. Generally, about five gas samples were taken for each test condition. The tar product, if any, was trapped in the 2-propanol solution. The rinsing solution was transferred to a ceramic tray and heated in an oven at 50ºC for about 12 hr to evaporate off any water and the rinsing solution. The collected tar product was weighed and the weight recorded. A calibrated flow meter was used to determine the flow rate of the producer gas. Measurement parameters such as fuel consumption rate, temperature at the different zones of the gasifier, producer gas temperature at the gasifier exit, and calorific value were constantly monitored. The gas composition was an average of the samples analysed during the tests. With this data, it was possible to calculate the gas heating value (HHV) from the combustion heat of the gas components:

$$HHV = \rho_N * \Sigma^{n}_{i} [\, x_i (- \Delta H^0_i) * 0.001 * M^{-1} \qquad (1)$$

where ρ_N is the specific mass (kg m^{-3}) at normal conditions (p = 101.325 kPa and t = 25ºC) and considering the ideal gas behaviour; x_i is the molar fraction of the i^{th} component, ΔH^0_i which is the standard combustion heat (J mol^{-1}); n is the number of components in the gas sample; M is the molecular mass (kg $kmol^{-1}$); and 0.001 is the conversion factor.

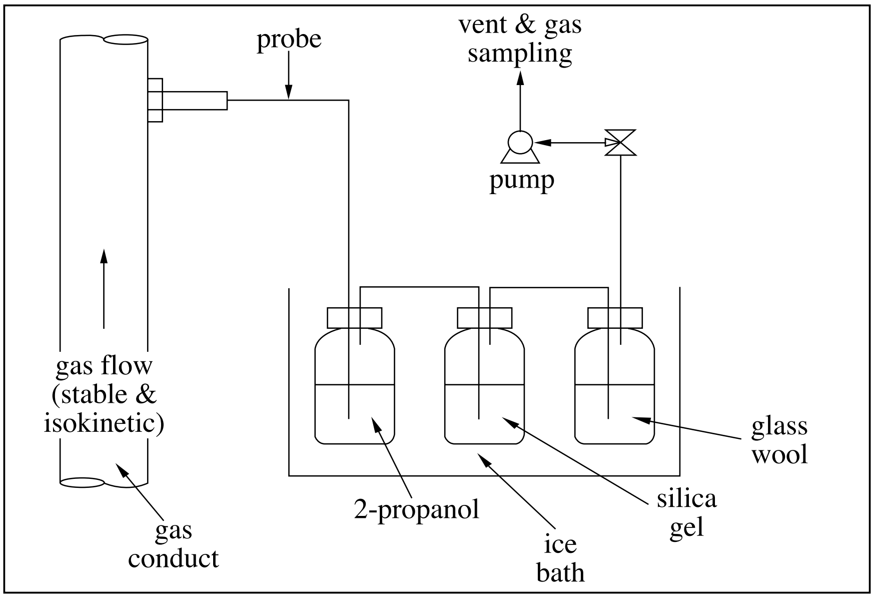

Figure 1. Schematic diagram of tar train sampling system.

RESULTS AND DISCUSSIONS

EFB from palm oil mill having a moisture content of 65% was further treated through shredding and hammer-milling as a size reduction process before feeding into the palm biomass downdraft gasification system. The pre-treated EFB with size reduced to 2-3 cm and further dried to about 15% moisture content were used in all the experiments. The warm-up time for the gasifier was about 30 min, during which the gases were emitted to the atmosphere through a gasifier chimney. The appearance of a steady and colourless flame, after 1 hr of operation gave an approximate indication that the gas was ready for use. The air-flow chosen for carrying out the gasification experiments had an equivalence ratio (ER), *i.e.* the ratio of mass of air to gasify 1 kg of fuel and the air required in kg for complete combustion of 1 kg of fuel, approximately in the range 0.28 to 0.43. This is in agreement with the equivalence ratio of 0.2-0.4 at a corresponding temperature range of interest at 700°C-1200°C for gasification, and 88%-90% of the total fuel energy is released either as chemical energy or as sensible heat at an equivalence ratio between 0.3 and 0.4 (Vimal and Bhatt, 1989). *Table 2* presents the fuel consumption rate with respect to gasification output constituent yields for EFB. The specific gasification rate, the amount of fuel that can be gasified per sq t grate per hour, in co-current gasifier systems with fixed grates was reported to be in the range of 100-200 kg m^{-2} hr^{-1} (Iyer *et al.*, 2002). In the present study, the specific gasification rate of EFB was observed to be 264 kg m^{-2} hr^{-1}, slightly higher than the reported value range. The temperature profile of gasification of EFB is shown in *Figure 2*. The steady-state conditions observed were reached between 60 and 210 min of the gasification process. Thus the steady-state conditions took a longer time to be reached compared to time taken for wood chips which was between 30 and 120 min, whereas for refuse-derived fuel the time was between 45 and 150 min of the gasification process (Rao *et al.*, 2004).

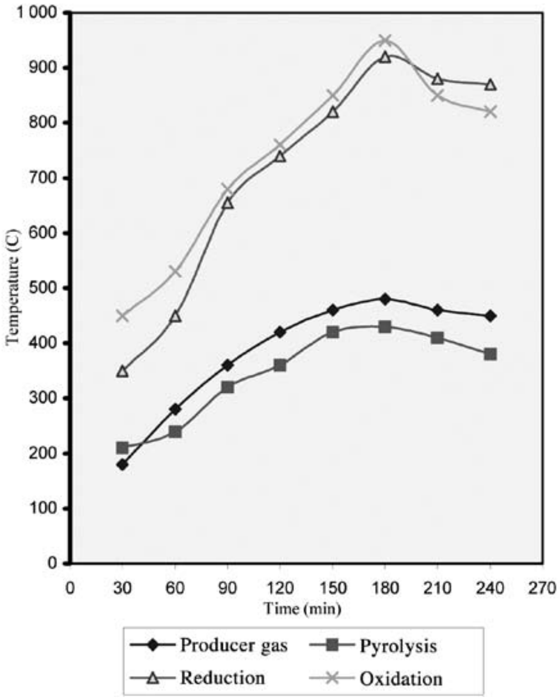

Figure 2. Temperature profile for pre-treated empty fruit bunches (EFB) gasification.

Gasification System Performance

The system was operated at an average gas flow rate of 60 Nm^3 hr^{-1}. The variations in the temperature of the different zones (pyrolysis, combustion and reduction) with respect to time were noted for all the experiments, and it was observed that the temperatures were almost constant. To maintain a uniform fuel flow in the gasifier, poking/ramming at regular intervals (30 min) was required. This may be due to the improper flow of fuel because of its low bulk density. The performance of the fixed bed gasifier was determined in terms of the cold gas and mass conversion efficiency, the flow rate of the producer gas and its calorific value. The quality of the producer gas depended on various factors such as moisture content of the feed, the airflow rate into the gasifier, the size of EFB and the reduction zone temperature. Gas analysis was used as a basis to determine the calorific value of the producer gas. A total of 10 runs were carried out in this study.

TABLE 2. GASIFIER AIR FUEL INPUTS

Empty fruit bunches (kg hr^{-1})	≈ 30
Air feed rate (secondary and primary air) (Nm^3 hr^{-1})	58.8-67.95
Air-fuel ratio (Nm^3 kg^{-1})	1.71-2.34

Gasifier Input Rate

The air and EFB inputs into the gasifier have been summarised in *Table 2*. The air-fuel ratio had a vital effect on the gasifier performance because it regulated the fuel consumption rate; therefore, the air-fuel ratio should be monitored carefully during the design of pilot-scale work in order to aid in scaling-up of the gasifier.

Gasification System Temperature

Temperature readings were taken once the system reached equilibrium when the producer gas started production. The results for each system are shown in *Table 3*.

TABLE 3. TEMPERATURES WITHIN THE GASIFICATION SYSTEM

Ambient air temperature	25ºC
Pyrolysis zone temperature	200ºC-300ºC
Oxidation zone temperature	600ºC-800ºC
Reduction zone temperature	750ºC-900ºC
Temperature gasifier exit	450ºC-500ºC
Temperature cyclone exit	180ºC-220ºC
Temperature scrubber exit	45ºC-55ºC
Temperature dryer exit	30ºC-40ºC

Effect of Operation Temperature on Gas Composition

Table 4 shows that the major combustible products were CO_2, hydrogen, methane and hydrocarbons. It was estimated that their total percentage amounted to approximately 26.5%-33.19% of the total product gas. The highest amount was obtained at its optimum operating point of feed rate, which was 30 kg hr^{-1}, and when the air-fuel ratio ranged from 1.71 to 2.34 Nm^3 hr^{-1}. There was a significant range in variation of the gas heating value from 4.3 to 5.2 MJ Nm^{-3} even under conditions of the same load and feedstock. These variations were due to changes in the stability of the feed system, in properties such as moisture content in EFB, and the rate of ash discharge. The production rate of the gas produced was in the range 2.6-3.2 Nm^3 kg^{-1} biomass. The gas composition ranged from 10.1%-12.4% carbon monoxide, 5.0%-6.6% hydrogen and 2.8%-3.7% methane. The system carbon conversion and cold gasification efficiency reached above 90% and 60%, respectively.

Table 4 indicates that the concentration of hydrogen and CO_2 increased with temperature and that the content of methane showed a decreasing trend, which implied more methane reacted with steam to produce the additional hydrogen. As the temperature increased from 750°C to 860°C, the gas yield increased from 2.6 to 3.2 Nm^3 kg^{-1} biomass (wet basis) and carbon conversion efficiency increased from 60.23% to 75.56%.

Gasification experiments were carried out at temperatures of 700ºC-950ºC. Treated EFB was fed into the system at a rate of 30 kg hr^{-1}. The

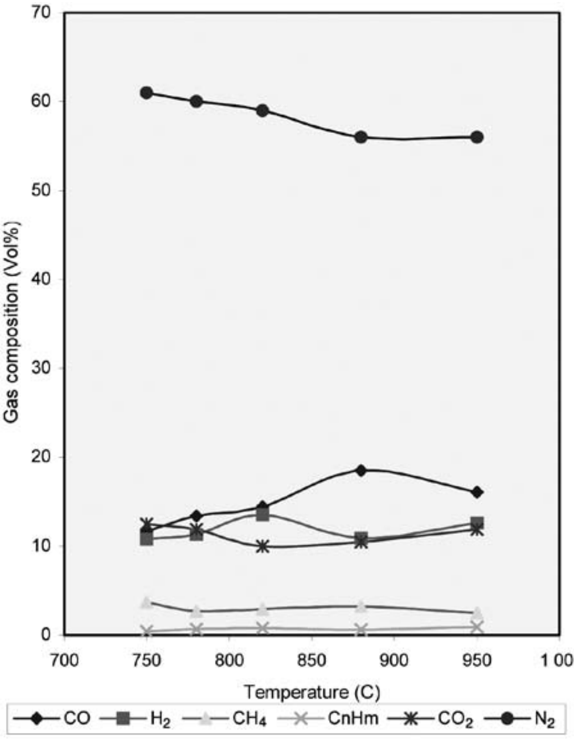

Figure 3. Variation of gas composition at optimum operating conditions and gasification temperature.

TABLE 4. GAS COMPOSITION IN GASIFIER BY RANDOM SAMPLING (Test 5)

Test 5
Air/EFB (Nm^3 kg^{-1}) = 2.24
Pre-heated air temperature = 400°C

Temperature (°C)		750	780	820	880	950
Gas composition (%)	CO	11.6	13.4	14.4	18.5	16.1
	H_2	10.8	11.3	13.5	10.9	12.6
	CH_4	3.7	2.7	2.9	3.2	2.5
	C_nH_m	0.4	0.7	0.8	0.59	0.9
	CO_2	12.5	11.9	10	10.5	11.9
	N_2	61	60	59	56	56
Gas heating value (kJ Nm^{-3})		4 228	4 022	4 543	5 196	5.129
Producer gas production (Nm^3 kg^{-1})		2.7	2.6	3.1	3.2	2.8
Carbon conversion efficiency (%)		73	85	86	88	90
Cold gas efficiency (%)		52	56	69	76	71

compositions of producer gas were detected at the air-biomass ratio at the optimum condition of 2.24 $Nm^3 kg^{-1}$. *Figure 3* shows that the concentration of carbon monoxide had an increasing trend at temperatures (T) < 880ºC and decreased slightly at T > 880ºC. The concentration of hydrogen showed slight changes when temperature was increased in the range of T < 820ºC, and dropped slightly in the range of T > 820ºC. The concentration of methane showed a slight declining trend as T > 750ºC and increased again at T > 880ºC.

Influence of Air-fuel Ratio on Fuel Gas Composition, Yield and Heating Value

The parameter that was used to control the operation of the proposed palm biomass downdraft gasifier was air-biomass ratio. The definition of this ratio is given in Equation (1):

$$\text{Air-biomass ratio} = \frac{\text{Total air added into the system (Nm}^3\text{)}}{\text{Total biomas fed into the system (kg)}} \qquad (1)$$

In view of the producer gas composition shown in *Table 5,* at the air-biomass ratio of 2.24 Nm^3 kg^{-1} (Test 5), the total combustible gas (CO + H_2 + CH_4) composition was 32.60% with CO, H_2 and CH_4 contents being 18.50%, 10.50% and 3.2%, respectively. The producer gas production was 2.97 Nm^3 kg^{-1}. As the air-biomass ratio increased to 2.34 Nm^3 kg^{-1} (Test 6), CO, H_2 and CH_4 contents were 15.20%, 13.20% and 3.40%, respectively, and the producer gas production was 3.20 Nm^3 kg^{-1}. The gas composition started to decrease when there was an increase in air-biomass ratio (Tests 11 and 14). However, the producer gas production showed an increasing trend at 4.34 Nm^3 kg^{-1} (Test 14).

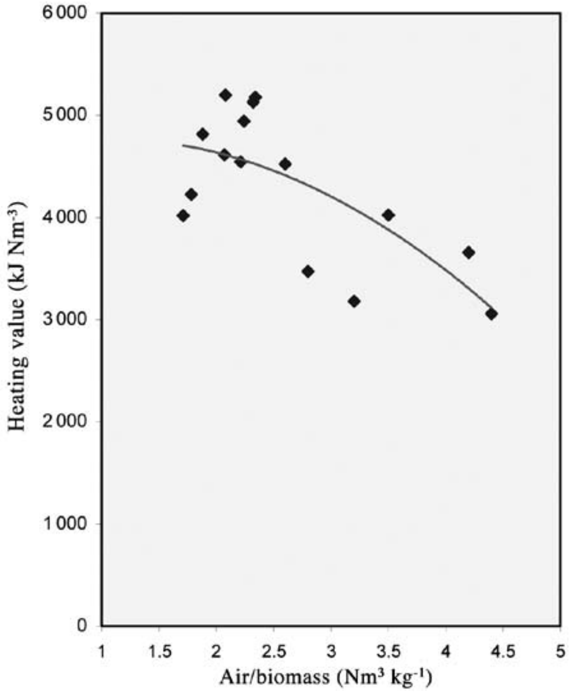

Figure 4. Variation in heating value of producer gas produced at different air-fuel ratios.

Due to higher heating value of methane and light hydrocarbons, the heating value of producer gas is expected to be as high as around 5000 kJ Nm^{-3}. The variation in heating value of the producer gas is shown in *Figure 4*, while the corresponding gas production is shown in *Figure 5*. A higher air-biomass ratio could result in a higher gasifier temperature and higher heating value, as indicated in Tests 5, 6 and 7. However, the gas composition started to deteriorate at a higher gasification temperature. In Tests 14 and 11, the

TABLE 5. GASIFICATION OPERATING PARAMETERS AND GAS PERFORMANCE QUALITY

Test	6	5	7	11	14
Gasification temperature (ºC)	870	880	850	900	950
Air-fuel ratio ($Nm^3 kg^{-1}$)	2.34	2.24	2.21	3.50	4.20
Gas production ($Nm^3 kg^{-1}$)	3.20	2.97	2.88	3.85	4.34
Carbon conversion (%)	88	88	85	70	68
Cold gas efficiency (%)	79	76	65	51	40
Heating value (kJ Nm^{-3})	4 946	5 196	4 616	3 475	3 182
Gas composition (vol.%)					
CO	15.20	18.50	14.40	9.50	7.30
H_2	13.20	10.90	10.70	3.40	3.30
CH_4	3.40	3.20	3.20	2.50	2.10
C_2H_4	0.50	0.80	0.65	0.80	0.80
C_2H_6	0.09	0.10	0.24	0.09	0.13
N_2	55	56	56	66	70
CO_2	12.60	10.50	12.80	17.00	16.30

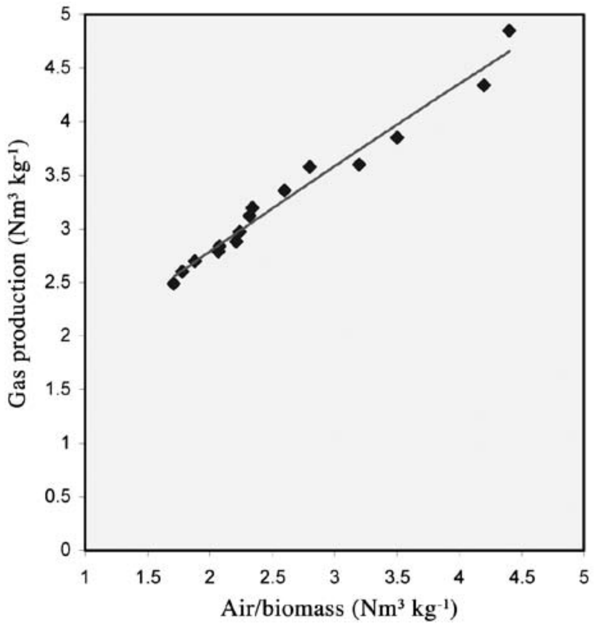

Figure 5. Variation in producer gas production at different air-fuel ratios.

total combustible gas decreased to about 12.70% and 15.40%, respectively. The heating value of the gas was reduced to about 3100 kJ Nm^{-3}. Thus, maintaining an optimum air-biomass ratio is critical in the designed biomass gasification.

Carbon Conversion and Cold Gas Efficiency

These two parameters can be used to investigate the effects of air-biomass ratio on the HHV of the producer gas. The definitions of carbon conversion efficiency (CCE) and the cold gasification efficiency (CGE) are shown in equations (2) and (3), respectively.

$$\text{Carbon conversion efficiency (CCE)} = \frac{\text{total reacted carbon in the system (kg)}}{\text{total carbon fed into the system (kg)}} \qquad (2)$$

$$\text{Cold gas efficiency (CGE)} = \frac{\text{HHV of producer gas (Nm}^3\text{ kg}^{-1}) \times \text{producer gas production (Nm}^3\text{ kg}^{-1})}{\text{HHV of biomass fed into the system (kJ kg}^{-1})} \qquad (3)$$

The variation in carbon conversion efficiency for the palm biomass gasification is shown in *Figure 6*. The carbon conversion of this system reached its maximum of 88% at an air-biomass ratio of about 2.24 Nm^3 kg^{-1}. Under conditions where air-biomass ratios ranged from 1.70-2.4 Nm^3 kg^{-1}, CCE was maintained at above 80%. However, under conditions where the air-biomass ratio was greater than 2.4 Nm^3 kg^{-1}, CCE started to decrease gradually (Tests 7, 11 and 14). The variation of CGE in relation to air-biomass ratio is shown in *Figure 7*. As the air-biomass ratio increased, as expected, CGE also increased. The reason is: more air was put into the gasifier to satisfy the needs of the gasification process of the palm biomass and its product. However, with additional air input into the reactor, CGE decreased starting at an air-biomass ratio of approximately 2.8 Nm^3 kg^{-1} due to the combustion of the gas.

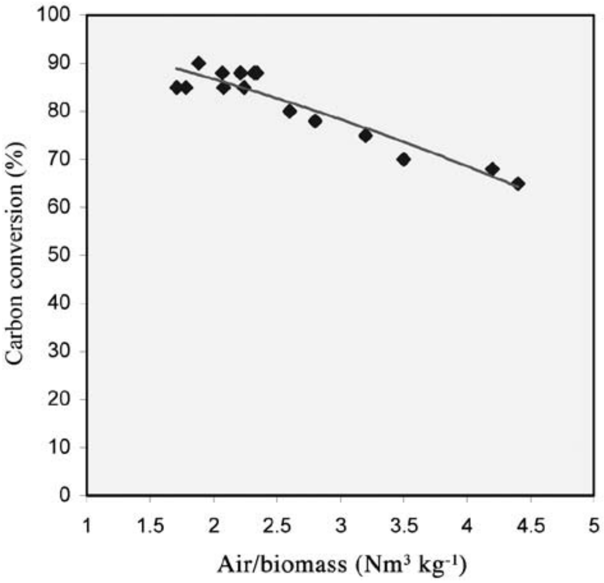

Figure 6. Variation in carbon conversion efficiency at different air-biomass ratios.

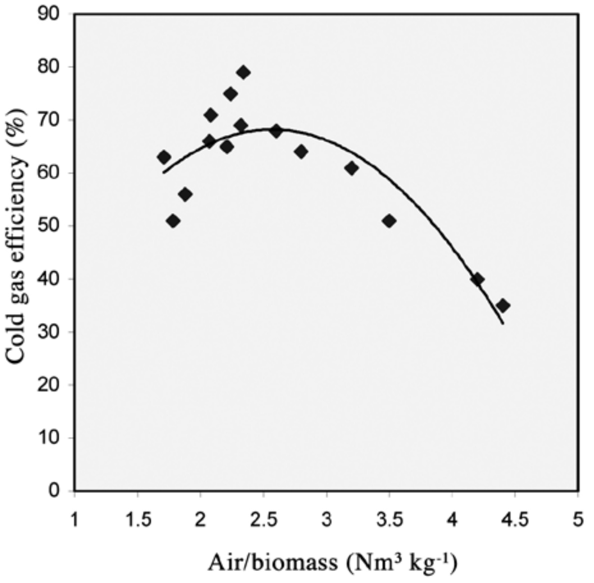

Figure 7. Variation in cold gas efficiency at different air-biomass ratios.

Temperature Profile *vs.* Tar Production

The effect of temperature variation at the reduction zone of the gasifier on tar production is

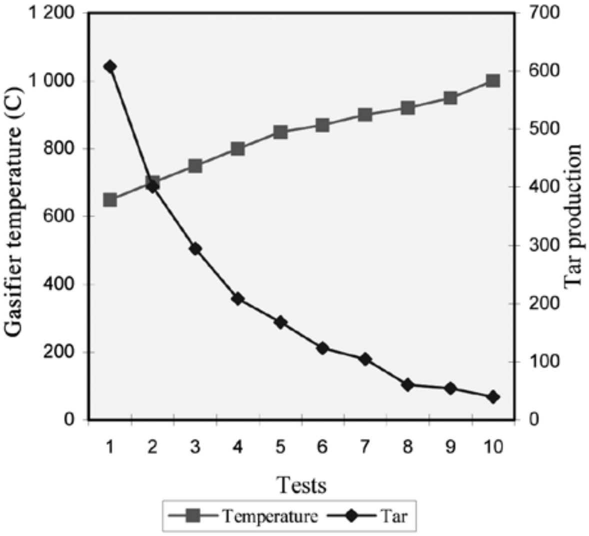

Figure 8. Temperature profile vs. *tar production.*

shown in *Figure 8*. It was observed that an increase in the temperature at the reduction zone of the gasifier from 700ºC to 980ºC could reduce tar production from 600 to below 50 mg Nm^{-3}. This figure satisfies the requirements for the gas to be used as fuel in an internal combustion engine. In order to make it safer for use in the engine, it is necessary to further treat the gas through the gas purification system where the tar content in the producer gas would be reduced further to below 15 mg Nm^{-3}. This tar content in the producer gas is comparable to those reported in the literature when using woodchips and rice husk as feedstocks.

Gas Purification System Performance

The level of contamination varies depending on the gasification process operation and the kind of fuel used. Therefore, the gas purification system is established to eliminate or reduce all contaminants (particulates, alkali metals, tars, hydrogen sulphide, hydrochloric acid, *etc*.) and to prevent erosion, corrosion and environmental problems in the downstream equipment, especially the internal combustion engines and gas turbines. The efficiency of each unit operation was estimated and shown in *Table 6*. From the proposed gas purification system, it is proven that the system can meet the demand of engines.

TABLE 6. MAIN CHARACTERISTICS OF THE GAS PURIFICATION SYSTEM

Parameter	Data
Efficiency of cyclone separator (%)	>85
Efficiency of Venturi wet-scrubber (%)	>80
Gas cleaning time (s)	8
Water consumption (litre hr^{-1})	10
Dimension of Venturi wet-scrubber (mm) (diameter × height)	500 × 1 500

CONCLUSION

In this study, the palm oil mill biomass gasification system was developed for producer gas production. The concept was demonstrated in a semi-pilot scale downdraft gasifier for producing quality bio-producer gas with higher heating value, using air as a gasification agent. The results from this innovative palm biomass gasification system show that the yield of producer gas ranged from 2.21 to 3.2 Nm^3 kg^{-1} biomass, and that the heating value of product gas was around 5.2 MJ Nm^{-3}. The upper region of the gasifier was maintained at a relatively high temperature to decompose the tar produced from the biomass pyrolysis and gasification process. The maximum temperature in drying, pyrolysis, and throat zones were determined as 125ºC, 350ºC, and 900ºC respectively, but the throat temperature fell to about 880ºC at the optimum. Carbon conversion efficiency and cold gas efficiency could reach 88% and 76%, respectively. The maximum total concentration of combustible fuel gas (H_2 + CO + CH_4) was 32.60% with concentrations of H_2, CO and CH_4 at 10.9%, 18.50% and 3.2%, respectively. The above results indicate that the innovative concept for palm oil mill biomass gasification proposed here looks quite promising, and that it could have potential in supplying an alternative energy resource in the near future.

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