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Design and Development of Laboratory Scale Updraft Gasifier for Gasification of Oil Palm Fronds

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ABSTRACT

The huge amount of wasted Oil Palm Fronds (OPF) produced annually provides a very good opportunity for the oil palm industry in Malaysia to use it for power generation, especially in mill boilers. Recently, gasification technology is receiving more attention as it can be used to convert wasted biomass into gaseous fuel for power generation and thermal applications as well as it can be used as a fuel source for the production of other chemicals. This study addresses the design, fabrication and performance evaluation of an updraft fixed-bed-gasifier. A 50 kW updraft gasifier is designed and fabricated for gasification of Malaysian oil palm fronds. The gasifier is designed using the empirical data from literature and derived quantities. The gasifier was modified to be very flexible allowing the gasification air to be fed through several locations. The air gasification results of OPF showed volumetric percentage of 22.61-23.36% of CO, 6.48-6.68% of H_2, 1.2-1.5% of CH_4, 9.51-9.65% of CO_2 and 59.20-58.1% of N_2. The heating value of the product gas mixture varied between 4.1-4.4 MJ Nm^{-3} while the cold gas efficiency, carbon conversion efficiency and specific gasification rate of the gasifier was in the range of 57-59 and 95-97% and 103-109 kg m^{-2} h^{-1}, respectively. The study has demonstrated that the oil palm frond waste is suitable for the designed and fabricated updraft gasifier and the produced gas from the gasification of OPF was successfully used in a domestic cooking stove.

Key words: Design, gasification, oil palm fronds, updraft gasifier

INTRODUCTION

Current energy suppliers in the world are dominated by fossil fuels (petroleum, coal and natural gas) which contribute to about 85% of the total global energy demand. However, the continuous growth of global energy consumption, high rate of fossil fuel depletion and rise of greenhouse emissions (CO_2) raises the problems related to energy availability, efficiency and safe operation (Rathore *et al.*, 2009). Moreover, energy related problems enhance the research for non-conventional sources of energy (Shuit *et al.*, 2009). As a tropical country and the highest producer and exporter of palm oil (Mohammed *et al.*, 2011), Malaysia generates a enormous amount of OPF as waste in the plantations during harvesting, pruning and replanting period and therefore, it is available on a daily basis (Zahari *et al.*, 2012). Availability is estimated at about 26 million tons $year^{-1}$ (Rahman *et al.*, 2011). Although, some efforts have been made to convert the fronds into valuable products such as production of animal roughage (Kawamoto *et al.*, 2001), pulp

and paper (Yakari, 2008), activated carbon (Salman and Hameed, 2010; Salman *et al.*, 2011) and renewable sugar (Fazilah *et al.*, 2009; Goh *et al.*, 2010), up to now most of the fronds are still left in the plantations mainly for nutrient recycling, soil conservation and erosion control (Mohideen *et al.*, 2011). As the OPF has slow degradation requiring a long time to decompose and remains long enough in the plantations causing mobility problems and to some extent threatening the life of the workers. In addition, the accumulation of OPF on the plantation lands causes environmental pollution problems (Salman *et al.*, 2011) and imbalance of nutrients in the soil. On the other side, the dumped rotted OPF may mix with rainwater resulting in harmful chemicals that may form a poisonous mixture known as leachate which percolates deep into the ground contaminating the ground water. Hence, the large quantities of OPF produced annually provide a very good opportunity for the oil palm industry to use it for power generation, especially for the mill boilers, consequently, reducing the environmental impact of having to treat this vast amount of waste. Gasification is one of the most promising technologies to convert carbonaceous material into gases such as H_2, CO, CO_2, CH_4 and traces of hydrocarbons by the supply of a gasification agent (Belgiorno *et al.*, 2003). The gasification process takes place in gasifers which is defined as devices or reactors for converting solid fuel into combustible gases. However, there are many types of gasifiers such as fixed bed gasifier, fluidized bed gasifiers and entrained bed gasifiers (Miskam, 2008). Among all the gasifier types, fixed bed updraft gasifier is mostly suitable for high-ash (up to 25%) and high moisture content (up to 60%) biomass fuel. It is also suitable for biomass with low volatile matter, possible to gasify biomass with large particle size and more suitable for direct combustion, where the producer gas is to be burnt in a furnace or boiler (Deshpande *et al.*, 2013). However, as the OPF is considered as low-density fuel, containing low volatile matter (compared to wood and empty fruit bunch) and having a relatively high ash percentage. Moreover, the fresh OPF is about 7-8 m in length (Aholoukpe *et al.*, 2013) and contains about 70% of moisture (Zahari *et al.*, 2012). Additionally, the updraft gasifier is simple in construction, flexible to deal with low quality biomass fuel in terms of suspended dust (Basu, 2010), has the highest biomass burn-out and internal heat exchange among all the types of gasifiers (Deshpande *et al.*, 2013), thus resulting in high gasification efficiency. Therefore, updraft gasifier is the most suitable option for gasification of OPF fuel in order to generate energy for thermal applications.

The main aim of this study is to examine the design, construction and performance of an updraft fixed bed gasifier, with oil palm fronds and air as the feedstock and gasifying medium, respectively.

MATERIALS AND METHODS

Feedstock material: The sample of the OPF used in this study was collected from Felcra oil palm plantation in Bota Kanan, Perak, Malaysia. Proximate and ultimate analyses as well as heating value of the OPF samples were carried out by using a Pyris 1 TGA analyzer (PerkinElmer), a Leco CHNS-932 elemental analyzer and an IKA Werke C5000 bomb calorimeter, respectively. The results of OPF characterizations are shown in Table 1. For gasification experiments, the freshly pruned OPF (after removing leaves) were cut and dried into the required size and moisture content. OPF with a size of about 5×5×10 mm and moisture content of about 20% (wet basis) was used in this study.

Design of updraft gasifier: Designing a gasifier means selecting the type of gasifier and obtaining the dimensions of all the components such as diameter, height, etc. In this study, an

Table 1: Characteristics of OPF fuel

Parameter	Value
Proximate analysis (wt.% dB)	
Moisture content	7.86
Volatile matter	68.32
Fixed carbon	18.77
Ash	2.25
Ultimate analysis (wt.% dB)	
C	42.48
H	4.52
N	0.61
S	0.05
O (by difference)	52.34
Higher heating value (MJ kg^{-1})	17.01

Table 2: Assumptions for updraft gasifier design

Description	Value	Remark
Gasifier output (P_g) (kW)	50	Assumed
Gasifier efficiency (η_g) (%)	70	Belonio (2005)
LHV of producer gas (LHV_g) (MJ m^{-3})	4	Basu (2010)
Specific gasification rate (SGR) (kg m^{-2} h^{-1})	110	Rathore *et al*. (2009)
Duty hours (T)	6	Assumed
Equivalence ratio (ϵ)	0.3	Belonio (2005)
Density of air (ρ_{air}) (kg m^{-3})	1.29	Belonio (2005)
Biomass molecular formula	$CH_{1.28}O_{0.92}$	Calculated
HHV of OPF (HHV_{OPF}) (MJ kg^{-1})	17.01	Measured

updraft gasifier was selected, designed and fabricated to study the gasification of oil palm fronds for thermal applications. Literature (Belonio, 2005) showed that most of the gasifier designs were based on empirical data, but there were many factors that should be considered for design in order to achieve the desired performance. They are the properties of the biomass feedstock, mode of operation, final use of producer gas, insulation of the reactor and the location of the firing.

Assumptions for gasifier design: Consideration was given to the characteristics of the feedstock, the power (capacity) of the gasifier and the end use of the gas generated from the gasifier. Recommended values for some parameters were obtained from the literature. Table 2 shows the assumptions made for the design of an updraft gasifier.

General calculations: As the expected output power of the gasifier is 50 kW, the power input (in terms of biomass fuel) can be determined as:

$$P_g = Q_i \times \eta_g \tag{1}$$

where, Q_i and P_g are the input and output power of the gasifier (kW) while η_g is the gasifier efficiency (%). Therefore, the input power was determined to be 71 kW. The fuel consumption rate which is the amount of energy needed for the gasifier in terms of biomass fuel in order to produce the required output power can be determined as follow (Van der Hoeven, 2007; Panwar and Rathore, 2008):

$$FCR = \frac{P_g}{LHV_{OPF} \times \eta_g} \tag{2}$$

where, FCR is the fuel consumption rate (kg h^{-1}) and HHV_{OPF} is the higher heating value of biomass fuel (MJ kg^{-1}). Therefore, the fuel consumption rate was determined to be 15 kg h^{-1}. The amount of Air Flow Rate (AFR) needed to gasify biomass fuel can be determined based on the fuel consumption rate, recommended equivalence ratio (ϵ), air density (ρ_{air}) and Stoichiometric air of biomass fuel (SA) as follow (Belonio, 2005):

$$AFR = \frac{\varepsilon \times FCR \times SA}{\rho_{air}} \tag{3}$$

The Stoichiometric Air (SA) can be determined as:

$$SA = \overline{AF}\left(\frac{M_{air}}{M_{fuel}}\right) \tag{4}$$

where, $\overline{AF}$ is the air to fuel ratio on molar basis, M_{air} and M_{fuel} are the molecular weight of air and fuel, respectively. The air to fuel ratio on molar basis was determined from the combustion reaction of oil palm frond in Eq. 5:

$$CH_{1.28}O_{0.92}+a(O_2+3.76N_2) = bCO_2+CH_2O+dN_2 \tag{5}$$

Thus, the constants a, b, c and d can be calculated from the elemental balance of carbon, hydrogen, oxygen and nitrogen. Therefore, the air to fuel ratio on molar basis and the stoichiometric air were determined to be 5.8 and 6.1 kg of air kg^{-1} of fuel, respectively. Based on that, the air flow rate was determined to be 21.3 m^3 h^{-1}.

Gasifier geometries: The gasifier diameter refers to the size of the gasifier in terms of the cross-section of the cylinder where the biomass fuels are being burned. As suggested by Belonio (2005) the gasifier diameter is a function of the amount fuel consumption rate and the specific gasification rate as described by the equation below (Belonio, 2005; Panwar and Rathore, 2008):

$$D = \left(\frac{4 \times FCR}{\pi \times SGR}\right)^{0.5} \tag{6}$$

where, D is the gasifier diameter which is determined to be 0.44 m in this case. Due to the difficulty of fabrication the gasifier and the cost involved, the cross sectional area was changed to the square shape according to the equation:

$$A = \frac{\pi}{4}D^2 = L^2 \tag{7}$$

where, A is the gasifier cross section area. The height of gasifier refers to the total distance from the top and the bottom end of the gasifier. This is a function of several variables such as

specific gasification rate, density of the biomass fuel and the time required to operate the gasifier as expressed below (Belonio, 2005; Panwar and Rathore, 2008):

$$H = \frac{SGR \times T}{\rho_{OPF}} \tag{8}$$

where, H, T and ρ_{OPF} are the gasifier height, time required to operate the gasifier and density of OPF, respectively. In view of above, the height of gasifier was determined to be 0.93 m, but the actual height was fixed at 1.2 m to serve two purposes. Firstly, to provide space at the top of gasifier for the accumulation of the producer gas and secondly, is to provide space at the bottom of the gasifier for ash collection.

Air nozzle design: Both high and low air velocities lead to formation of central dark zone in the oxidation zone and inefficient tar cracking. The area (size and number) of the nozzles can be calculated using the equation below:

$$\alpha = \frac{AFR}{v} \times \frac{10^3}{3.6} \tag{9}$$

where A_{noz} and v are the cross section areas (mm^2) of the nozzles and the air velocity (m sec^{-1}), respectively. Assuming that the air velocity is 8 m sec^{-1} which is recommended for updraft gasifier (Ramana *et al.*, 2005; Rowland, 2010), the area of the nozzles should be about 0.739 mm^2.

Fabrication of updraft gasifier: The gasifier was fabricated in a local workshop. The chamber of the gasifier was constructed from mild steel and refractory cement. However, the internal and external walls were made from mild steel (4 mm thickness) with a gap of 17 mm between the mild steel walls as shown in Fig. 1a. This gap of 17 mm was filled with refractory cement as shown in Fig. 1b. The purpose of the refractory cement is to reduce the heat loss from the gasifier. The

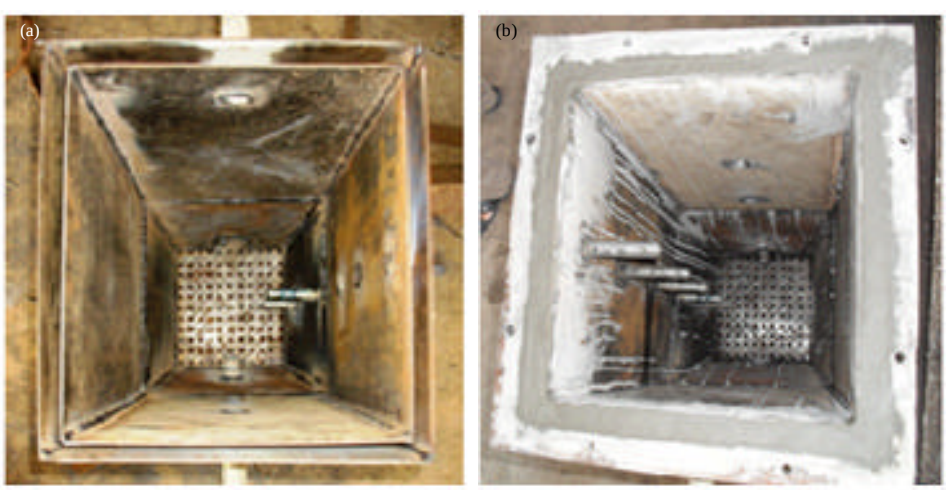

Fig. 1(a-b): (a) Semi-finished gasifier chamber and (b) Refractory cement insulation of gasifier chamber

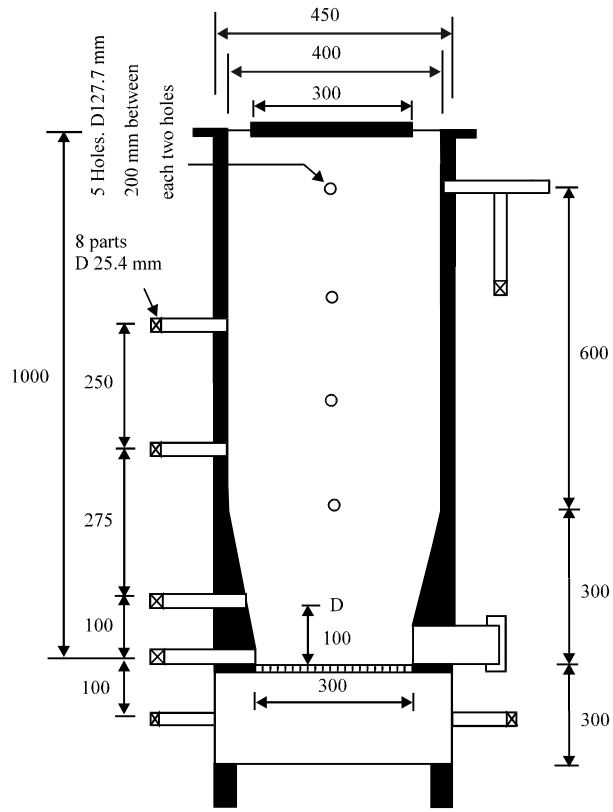

Fig. 2: Designed updraft gasifier (all dimensions in mm)

gasifier has one opening on top for the feeding of fuel. The gasifier was provided with four nozzles for feeding gasification air. Two of them are located 100 mm below the grate, the third nozzle is located immediately above the grate (named, through the grate) while the last nozzle is located at about 100 mm above the grate. Two more nozzles with the same diameter are constructed at 375 and 625 mm above the grate (Fig. 2). The nozzles at about 100, 375 and 625 mm above the grate enable study of the effects of varying inlet position of secondary air on the gasification process. Those points represent a mid of combustion, reduction and pyrolysis zones, respectively.

The lower portion of the gasifier includes the grate, two inlet air nozzles, ash receptacle and ash cleanout port. The grate was made of mild steel and was directly suspended on the combustion zone to allow the ash fall through, without loss of fuel. Moreover, the grate is used as an air distributor; however the holes are distributed across the whole section of the grate as shown in Fig. 1. The ash receptacle was made in square shape and fixed below the grate and had a height of 200 mm and an outside length of 450 mm.

The upper part of the gasifier includes the feedstock feeding portion and the producer gas exhaust pipe. The feeding portion was in square shape and had a cross section area of about 0.09 m^2. The producer gas exhaust pipe was made of Galvanized pipe (GI pipe) and it included three sections. The first was a dirt leg which is used for tar and condensate removal while the second was a temperature probe to measure the temperature of the outlet syngas. The last was a pipe with a ball valve which is used to check the combustibility of the producer gas (named, flare point No. 1).

Experimental set-up and procedure: The experimental setup used in this study consisted of the components shown in Fig. 3. The gasification experiments were performed at air flow rate of about 16.8 m^3 h^{-1}. Two types of experiments were conducted. In the first experiment, the air was introduced to the gasifier through a single feeding point at about 100 mm below the grate while in the second experiment; the air was introduced to the gasifier through two feeding points at about 100 mm below the grate. The experiments were performed in an atmospheric batch type updraft gasifier. The temperature inside the gasifier was measured by five type-K thermocouples (T_1 is measured at 100 mm, T_2 at 300 mm, T_3 at 500 mm, T_4 at 700 mm and T_5 at 900 mm above the grate) while the temperature of the generated gas was measured at was measured by other thermocouple (T_6). The air (gasification agent) flow rate was measured by using a flowmeter (Dwyer flometer, Model: VFC-131). The producer gas was filtered, cooled and then sampled for analyzing. The analysis of the producer gas was carried out at five minute-interval during the experiment run till the end of the experiment by using online gas analyzer (Emerson X-STREAM gas analyzer, Germany). Initially, the gasification tests started by uploading the gasifier with charcoal to preheat the gasifier (up to 600°C), then the batch sample (12 kg) of the OPF was added to the gasifier through the top and the air was adjusted to the required experimental conditions and then finally the gasifier cover was closed.

The gasification parameters such as gas calorific value (MJ Nm^{-3}), gas production yield (Nm^3 kg^{-1}), cold gas efficiency (%) and carbon conversion efficiency (%) as well as specific gasification rate (kg m^{-2} h^{-1}) were estimated as shown in Eq. 10-14), respectively:

$$\text{Gas heating value} = \sum \text{volume\% of component} \times \text{heating value of the component} \tag{10}$$

$$Y_{gas} = \frac{Q_{air} \times 0.79}{\dot{m}_{OPF} \times N_2\%} \tag{11}$$

where, Y_{gas} is the fuel gas production, N_2% represents the N_2 concentration in the fuel gas. Q_{Air} and $\dot{m}_{OPF}$ represent flow rate of air (Nm^3 h^{-1}) and OPF consumption rate (kg h^{-1}), respectively:

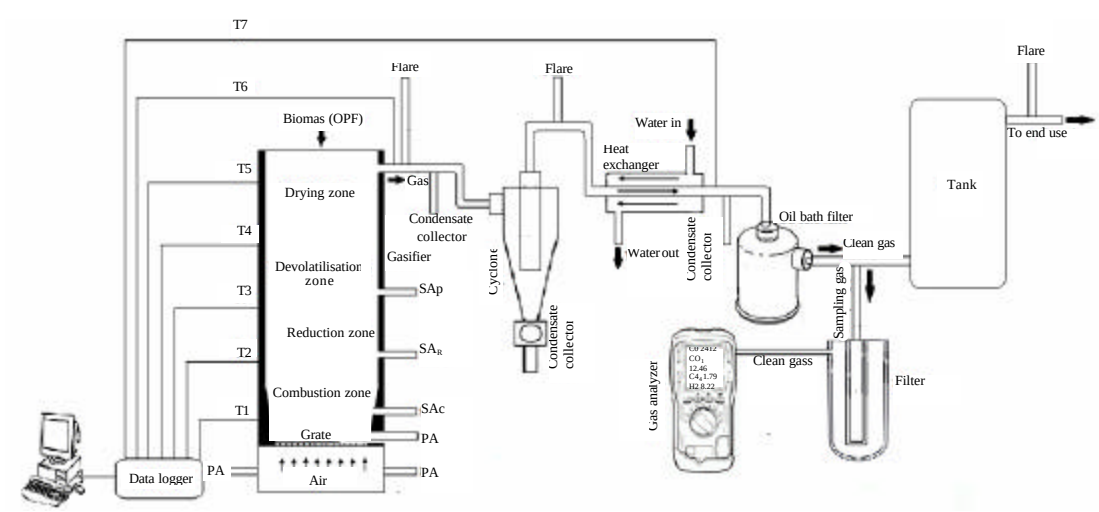

Fig. 3: Schematic diagram of an updraft gasification system

$$\eta_C = \frac{12 \times Y_{gas} \times (CO + CO_2 + CH_4)}{22.4 \times C\%} \quad (12)$$

where, η_c represents the carbon conversion efficiency and C% is air dried based carbon content in OPF ultimate analysis:

$$CGE = \frac{Y_{gas} \times HHV_{gas}}{HHV_{OPF}} \quad (13)$$

where, CGE is the cold gas efficiency, HHV_{gas} is the higher heating value of the producer gas and HHV_{OPF} is the higher heating value of the fronds and finally the specific gasification rate is defined as:

$$SGR = \frac{\dot{m}_{OPF}}{A} \quad (14)$$

where, A is the gasifier cross-sectional area (m^2).

RESULTS AND DISCUSSION

Gasifier performance: As mentioned earlier, the temperature inside the gasifier was measured at different locations by using a set of thermocouples (Fig. 3). The temperature distribution throughout the height of the gasifier is shown in Fig. 4a-b. It is observed that after about 10 min from the starting, constant temperature at T_1 was observed, indicating the stability of gasification process as shown in Fig. 4a-b. As the height from the grate was increased, the temperature decreased due to heat energy produced at the oxidation zone was being used by the endothermic reactions of the other gasification zones. It was also observed that introducing the air through two feeding points below the grate resulted in more uniform and higher temperature at the oxidation zone as shown in Fig. 4b. This might be attributed to introducing the air through two feeding points resulted in better air distribution across the grate cross-sectional area.

Figure 4c-d show the dry gas composition for both cases. The average value of the producer gas was found in the range of 22.61-23.36% of CO, 6.48-6.68.04% of H_2, 1.2-1.5% of CH_4, 9.51-9.65% of CO_2 with an average heating value in the range of 4.1-4.4 MJ kg^{-1}. The other gasification parameters such as dry gas yield, carbon conversion efficiency, cold gas efficiency and specific gasification rate was found in the range of 2.29-2.36 Nm^3 kg^{-1}, 95-97, 57-59% and 103-109 kg m^{-2} h^{-1}, respectively. The results obtained from this study were compared with that obtained from updraft gasification of beech wood, wood pellets, Refuse Derived Fuel (RDF) pellets and sewage sludge as shown in Table 3. The OPF showed a heating value less than that obtained for wood and RDF while it shows a heating value higher than that obtained from sewage sludge. This may be due to the difference in higher heating value of the original biomass. As the heating value of wood and RDF are higher than that of OPF while the heating value of sewage sludge is lower than that of OPF.

It is also observed that the producer gas was started to be generated after about 10-15 min from starting the experiments (after stability of gasification process). To examine the capability of OPF synthetic gas as a fuel for power generation and heat applications, the produced gas has been flared through three provided ports in the system. However, the first flare point (Fig. 5a) was

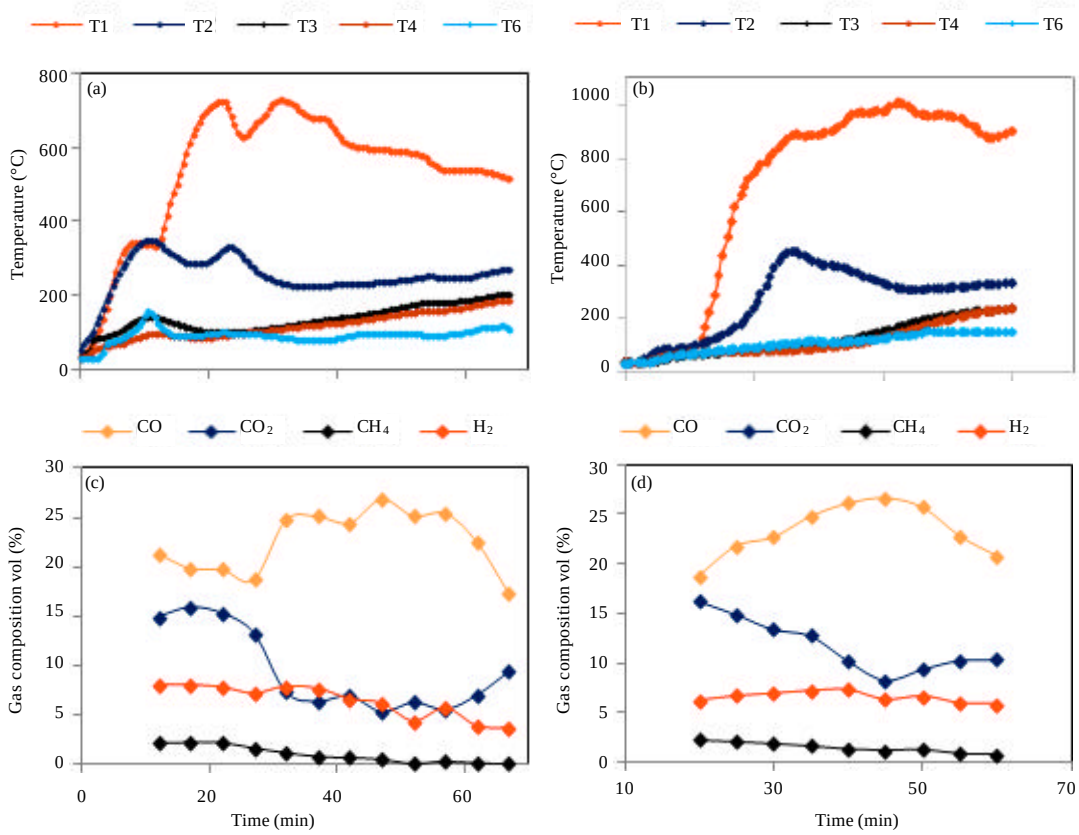

Fig. 4(a-d): Temperature profiles and syngas composition with time for experimental 1 and 2 (a-b) Temperature distribution across the gasifier and (c-d) Syngas composition with time

Table 3: Comparison of OPF air gasification results with literature results of air gasification of different feedstock

	Gas composition vol. (%)										
Fuel	CO	CO_2	CH_4	H_2	HHV (MJ Nm^{-3})	Y_{gas} (Nm^3 kg^{-1})	CCE (%)	CGE (%)	SGR (kg m^{-3} h^{-1})	ER	References
OPF	23.36	9.65	1.50	6.68	4.40	2.29	95	59.10	109	0.36	Current study
Beech wood	30.00	7.00	2.00	8.00	5.50	na	na	na	na	na	Di Blasi *et al*. (1999)
Wood pellets	27.47	6.22	1.88	7.13	4.99	na	na	51.2	na	na	Plis and Wilk (2011)
RDF pellets	25.50	5.30	1.00	18.50	5.58	2.35	na	73.18	196	0.35	Rao *et al*. (2004)
Sewage sludge	11.20	12.70	1.10	4.40	3.96	0.51	na	21.0	na	0.15	Seggiani *et al*. (2012)

HHV: Higher heating value, Y_{gas}: Gas yield prodnction, CCE: Carbon conversion efficiency, CGE: Cold gas efficiency, SGR: Specific gasification rate, ER: Equivalence ratio, OPF: Oil palm frond, RDF: Refuse derived fuel

located at the producer gas exhaust pipe and the second flare point (Fig. 5b) was located at the exit pipe of the cyclone while the last point (Fig. 5c) was located at the exit of the accumulation gas tank. As shown in Fig. 5a-c, the producer gas was able to be flared at the three points with different phenomena.

Fig. 5(a-c): Producer gas flared at exit of (a) Gasifier, (b) Cyclone and (c) Accumulation tank

Table 4: Total mass balance during air gasification of oil palm fronds

	Mass input (kg h^{-1})		Mass output (kg h^{-1})				
OPF	Air	Total	Syngas	Char-ash	Condensate	Total	Closure
9.23	20.16	29.39	26.25	0.41	0.21	26.87	0.914
9.83	20.20	29.99	28.14	0.58	0.22	28.94	0.965

OPF: Oil palm fronds

Mass and energy balance: The total mass balance was carried out to examine the reliability and to validate the experimental gasification data. The mass inputs include the feedstock and air while the mass outputs comprise of dry gas product, char-ash and condensate as shown in Table 4. The mass balance closure which is defined as the percentage of the total mass output to that of the total mass input was observed to be in the range of 91-96%, with an average of about 95%. This result indicates the reliability of collected data measurements. An overall mass balance closure of 100% is not easy to obtain, due to the leakage of the system, error in measurements and assumptions that are taken into account in the calculation of the mass balance.

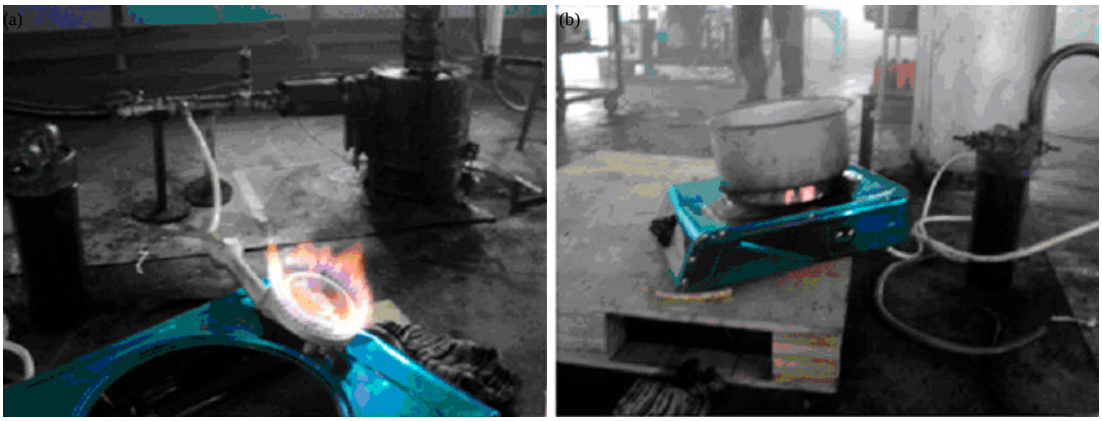

Fig. 6(a-b): Use of OPF synthetic gas (a) Synthetic gas flare in the stove burner and (b) Boiling water with domestic cooking stove

Producer gas utilization: In order to investigate the possibility of using the OPF synthetic gas for thermal applications, the produced gas was used in a domestic cooking stove for boiling water from ambient temperature. The stove used in this experiment was not designed specifically to be used with the synthetic gas. It was designed to be used with domestic cooking gas (Liquefied Petroleum Gas, LPG). Initially, the stove was disassembled and then the produced gas was ignited in the burner by showing the flame through the holes in the burner as shown in Fig. 6a. Thereafter, the stove was assembled and then connected to the supply of the gas as shown in Fig. 6b.

In the water boiling test, the producer gas with a known flow rate (15 LPM) was allowed to flow naturally to the stove burner and then the stove was ignited by cigarette lighter. Thereafter, a known quantity of water (1.0 L) was taken in a cooking pot and then put in the stove stand and left to boil as shown in Fig. 6b. The time for boiling the water was then used to estimate the energy used for boiling the water.

The water in the pot was boiled in about six minutes consuming about 0.09 m^3 of the OPF synthetic gas. As mentioned earlier, the gas yield was about 2.29 $Nm^3\ kg^{-1}$ of OPF. Therefore and via updraft gasification technology, each kilogram of OPF was expected to boil about 25 L of water. The energy needs to boil water can be determined as follows:

$$\text{Energy} = \text{Specific heat of water} \times \text{mass} \times \text{temperature rise} \tag{15}$$

Hence, the energy needed to boil 25 L of water was found to be 8.37 MJ. Theoretically, the Malaysian LPG has a calorific value of about 45.9 MJ kg^{-1}. Therefore, via., updraft gasification each kilogram of OPF could save about 0.2 kg of LPG.

CONCLUSION

A 50 kW batch type updraft gasifier was designed and constructed from mild steel and cement refractory as lining wall and insulation, respectively. The designed and developed gasifier operates remarkably with the OPF as a feedstock. The gas produced from air gasification of oil palm fronds

was found in the range of 22.61-23.36% of CO, 6.48-6.68% of H_2, 1.2-1.5% of CH_4, 9.51-9.65% of CO_2 and 59.20-58.9% of N_2 with higher heating value ranged from 4.1-4.4 MJ Nm^{-3}. The average results of overall mass balance closure were observed to be about 95%, indicating the reliability of collected data. The gas produced from the gasification of OPF in updraft gasifier was flared with stable blue colour flame through the whole test period; moreover the product gas was successfully used in a domestic cooking stove.

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