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Combustion of oil palm stone in a pilot-scale fluidised bed reactor

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ABSTRACT

Biomass is being generated in vast amounts from oil palm plantations particularly in developing countries such as Malaysia, Thailand and Indonesia. Oil palm stone (OPS) is currently considered a waste material and has not previously been considered for energy purposes. The main objective of this study was to investigate the thermochemical conversion of OPS in a pilot-scale fluidised bed combustor. The net heating value of OPS was 24.93 MJ/kg. The effect of primary air flowrate and initial bed temperature were the main parameters investigated. The bed and bed's surface temperature were found to decrease as the primary air flowrate increased. In all tests CO emissions were less than 0.2%. The emissions of SO_2 and HCl ranged from 0.02 ppm to 0.05 ppm, significantly below the permitted levels set by legislation. Stable combustion was observed at a bed temperature of 950 °C. The most abundant elements found in the ash were Al, Ca, Fe, K, Mg, Mn, P, S and Si. However, due to the temperature regime used in the study fouling would not be an issue.

1. Introduction

Biomass is a promising source of fuel for energy generation, contributing over 14% or 1250 million TOE of the global energy demand annually [1]. Most of the biomass production and utilisation are concentrated in developing countries. It is estimated that around 75% of biomass energy is used in developing countries and approximately 25% is consumed by industrialised nations [2]. Some biomass fuels such as woody biomass and energy crops are already important energy carriers in meeting the world's energy demand [2].

Utilisation of biomass fuel could help to mitigate climate destabilising emissions, particularly on issues related to global warming or greenhouse gases (GHG). Carbon dioxide (CO_2) emissions from burning fossil fuels is one of the major sources of GHG emissions and have rapidly increased in the last few decades particularly due to the burning of fossil fuels in power plants [3,4]. Global CO_2 emission will increase at a rate of 1.7% annually if present production and consumption trends continue [5]. According to Safaai et al. [3] by the year 2020 Malaysia could produce almost 260 million tonnes of CO_2 if there are no regulations imposed by the government to mitigate release. As the world's second largest palm oil producer and exporter Malaysia has potential to produce significant amounts of sustainable biomass for clean energy generation. Following environmental pressure, the Malaysian government has recognised this by making biomass the fifth fuel in the nation's energy mix from the year 2000 [6,7]. This has helped reduce the demand for fossil fuels and started the mitigation process against GHG emissions, particularly CO_2 gas.

Shells, fibres and palm kernel, among others, are the most abundant solid wastes produced during palm milling processes [8]. Shuit et al. [7] revealed that as much as 50–70 tonnes of biomass waste can easily be produced in 1 ha of oil palm plantation. With this capacity, Malaysia could potentially generate about 56 million tonnes of biomass, which is equivalent to about 16 Mtoe per annum [7]. Much of this waste is left to decay in plantation areas or used as soil conditioner [9]. Utilising waste from the oil palm industry, particularly the oil palm stone (OPS), for energy purposes could help Malaysia further mitigate CO_2 emissions [10].

The design of the combustion vessel or reactor and properties of the fuel are important considerations in achieving a high thermal efficiency. Therefore, understanding what happens to particles of solid fuel during the combustion process is of key importance. Biomass particles undergo a process of heating up, drying, and devolatilisation before combustion of volatile matter and the char [1]. Werther et al. [1] showed that volatile and moisture contents of biomass fuels have a significant effect on combustion and thus on the design and operation of the reactor. Thermochemical biomass conversions based specifically on combustion efficiency using different combustion systems such as grate-fired, fluidised bed and suspension fired have been thoroughly reviewed in literature [1,10–18]. The authors generally agreed that fluidised bed technology is the most efficient and suitable for converting fuels with low calorific value due to its flexibility, high efficiency and low impact on environmental problems. The release of gases from biomass combustion is affected by several factors including fuel chemistry, moisture content, particle size, particle shape and the combustion processes [19]. The principal gases released during combustion of biomass are CO_2 and water, the products of complete combustion. CO_2 emitted from biomass combustion is considered to be CO_2-neutral as a GHG where sustainable crops are used. Other

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gases and residues may be released during combustion processes including CO, char, tar, polycyclic aromatic hydrocarbons, and other organic compounds as well as NOx, SOx, HCl and ash particles. These environmental pollutants can be treated by manipulating the combustion parameters or adopting gas or particulate cleaning systems.

The main objective of this research was to characterise the properties of oil palm stone (OPS) for use as fuel based on proximate and ultimate analyses and to examine the effects of combustion parameters on the thermochemical behaviour of OPS in a pilot-scale fluidised bed reactor. The variables investigated included the effects of primary air flowrate and initial temperature of the bed when feeding commenced on temperature profiles throughout the reactor as well as gas emissions. Ash residue and acid gases were also analysed in order to obtain a better understanding of OPS combustion in a pilot-scale fluidised bed reactor.

2. Materials and methods

2.1. OPS characterisation

The OPS used for these experiments was supplied by A.M.E. Teras Marin Services Ltd., Malaysia. The sample, Fig. 1, was air dried at room temperature following receipt. Standard analytical tests were then carried out on this material. Table 1 shows the calorific value and the results of the proximate and ultimate analyses for the OPS. The material had a very high volatiles content (88.21 wt.%), with a small amount of fixed carbon (7.24 wt.%). The net calorific value (LHV) of the OPS was measured around 24.93 MJ/kg. The LHV was found to be similar to that of lignite (26.80 MJ/kg) [20]. Ultimate analysis indicated that OPS has a very low sulphur content which would reduce the requirement for costly post-combustion SOx reduction technologies.

The thermal characteristics of dry OPS sample were analysed with a computerised Perkin-Elmer Pyris 1 thermogravimetric analyser (TGA). The experiments were carried out with the following conditions; about 5 mg of sample was heated at a rate of 5 °C/min from 50 to 800 °C. Oxygen-free nitrogen gas was used as the carrier. Fig. 2 shows the results for two TGA tests for the thermal degradation of OPS. Two main decomposition peaks were identified at 290 °C and 350 °C. These peaks are thought to be due to the decomposition of hemicelluloses and cellulose respectively [21]. Low weight loss was observed at temperatures up to 250 °C due to the release of the moisture content. A rapid loss in weight was achieved between 250 °C and 380 °C due to the release of volatile matter and decomposition of water. At elevated temperatures, >380 °C, the loss in weight decreased steadily mainly associated to liberation of hydrogen gas. The total weight loss between 28 °C and 380 °C was observed to be 88 wt.%. About 10 wt.% remained as char residue.

Fig. 1. Oil palm stone (OPS).

Table 1
Experimentally determined gross calorific value and proximate and ultimate analyses of oil palm stone.

Analysis		Oil palm stone
Proximate (%, as received)	Moisture	2.85 (±0.15)
	Ash	1.70 (±0.05)
	Volatiles	88.21 (±0.20)
	Fixed carbon	7.24 (±0.09)
Ultimate (%dry, ash-free)	C	66.06 (±2.44)
	H	10.86 (±0.25)
	O	21.06 (±2.16)
	N	1.65 (±0.08)
	S	0.36 (±0.33)
Net calorific value (MJ/kg)		24.93 (±0.21)
Density (kg/m^3)		630 (±10)
Average diameter (m)		0.01 (±0.05)

Table 2 shows the main elements obtained from OPS sample analysed using inductively coupled plasma-optical emission spectroscopy (ICP-OES). High concentrations of potassium (K) and phosphorus (P) were found and thought to be due to the presence of potassium nitrate (KNO_3) and phosphoric acid (H_3PO_4) that have been used in fertilisers [22]. High alkali metal contents in fuels can be problematic during combustion as they lower oxide melting/fusion temperature which leads to an increase in boiler fouling deposits [8,23]. OPS was found to contain significantly low concentrations of toxic and heavy metals such as antimony (Sb), arsenic (As), and lead (Pb).

2.2. Experimental facilities and conditions

2.2.1. Experimental set-up

The combustion tests were carried out in pilot-scale fluidised bed reactor. The combustor was made of 306 stainless steel 2.3 m × 0.15 m, 10 mm thick. A 10 mm thick stainless steel perforated distributor plate was used to distribute the primary air, located 200 mm from the base of the reactor as shown in Fig. 3. Nineteen 6 cm high with 45° angle capped standpipes covered the surface of the plate. Each pipe consisted of twenty-seven 1.5 mm diameter holes to evenly distribute the primary air, which acted as both the fluidising and combustion air. An average of 850 μm diameter medium sphericity sand was used as the inert bed material. The depth of the sand bed on the distributor plate was 250 mm. A propane-fired pilot burner was used to preheat and stabilise the sand bed temperatures during the reactor's start-up mode. In order to provide isothermal conditions the reactor was insulated using Kaowool blanket material

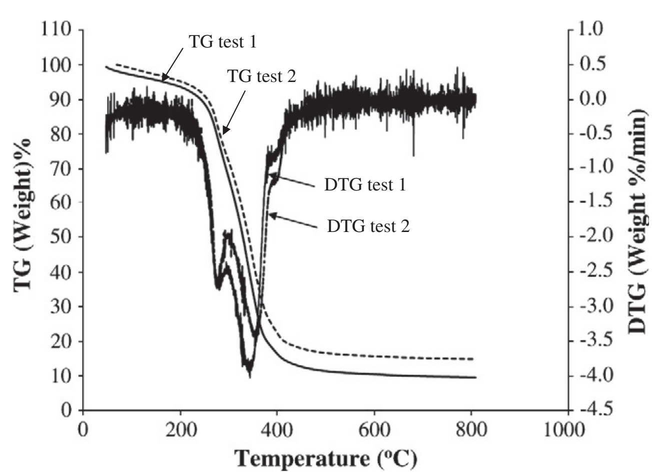

Fig. 2. Thermal degradation behaviour by TGA of OPS sample.