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Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor

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ABSTRACT

A study on gasification of empty fruit bunch (EFB), a waste of the palm oil industry, was investigated. The composition and particle size distribution of feedstock were determined and the thermal degradation behaviour was analysed by a thermogravimetric analysis (TGA). Then fluidized bed bench scale gasification unit was used to investigate the effect of the operating parameters on EFB air gasification namely reactor temperature in the range of 700–1000 °C, feedstock particle size in the range of 0.3–1.0 mm and equivalence ratio (ER) in the range of 0.15–0.35. The main gas species generated, as identified by a gas chromatography (GC), were H_2, CO, CO_2 and CH_4. With temperature increasing from 700 °C to 1000 °C, the total gas yield was enhanced greatly and reached the maximum value (~92 wt.%, on the raw biomass sample basis) at 1000 °C with big portions of H_2 (38.02 vol.%) and CO (36.36 vol.%). Feedstock particle size showed an influence on the upgrading of H_2, CO and CH_4 yields. The feedstock particle size of 0.3–0.5 mm, was found to obtain a higher H_2 yield (33.93 vol.%), and higher LHV of gas product (15.26 MJ/m^3). Equivalence ratio (ER) showed a significant influence on the upgrading of hydrogen production and product distribution. The optimum ER (0.25) was found to attain a higher H_2 yield (27.31 vol.%) at 850 °C. Due to the low efficiency of bench scale gasification unit the system needs to be scaling-up. The cost analysis for scale-up EFB gasification unit showed that the hydrogen supply cost is RM 6.70/kg EFB ($2.11/kg = $0.18/$Nm^3$).

1. Introduction

Dependence on fossil fuels as the main energy sources has led to serious energy crisis and environmental problems. Therefore, due to the environmental considerations as well as the increasing demand for energy in the world, more attention has been paid to develop new energy sources [1]. Owing to that, there has been interest in the utilization of biomass for production of environmental friendly biofuels. As known, biomass is a CO_2 neutral resource in the life cycle, while CO_2 is a primary contributor to the global greenhouse effect. Hence, increasing attention is being paid to biomass as a substitute for fossil fuel to reduce the global greenhouse effect, particularly under the commitment of the Kyoto Protocol. Biomass used as an energy resource can be efficiently achieved by thermo-chemical conversion technology: pyrolysis, gasification or combustion. Gasification process is one of the most promising thermo-chemical conversion routes to recover energy from biomass. During gasification process, biomass is thermal decomposed to small quantities of char and ash, liquid oil and high production of gaseous products under limited presence of oxygen following Eq. (1). The yields of end products of gasification and the composition of gases are dependent on several parameters including temperature, biomass species, particle size, heating rate, operating pressure and reactor configuration [2].

$$\text{Biomass} + \text{heat} \rightarrow H_2 + CO + CO_2 + CH_4 + \text{Hydrocarbon} + \text{Char} \quad (1)$$

The concern of using biomass in gasification to produce a hydrogen rich product has been getting particular attention in recent years. The reasons may be attributed to: (1) hydrogen is a clean and efficient energy source and is expected to take an important role in a future energy demand; (2) hydrogen is a safe source and can be easily stored as a gas or a liquid; (3) hydrogen has good properties in fuelling engines in automobiles; and (4) most important, current and future energy technologies are extensively increasing the possibility of utilizing hydrogen with economic acceptance. Apparently, how to force the biomass gasification process into shift towards the maximum hydrogen rich end product is becoming a priority topic [3].

Various types of biofuels can be produced from gasification process after catalytically upgrading the syngas by using Fischer–Tropsch (FTS) synthesis and Higher Alcohol synthesis (HAS) technologies [4]. Through the FTS reaction, syngas can be

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converted to a wide range of long chain hydrocarbon products, like gasoline, naphtha, diesel and wax. The long chain hydrocarbons produced from the FTS reaction are distilled and hydro-cracked before being used as a liquid transportation fuel [5]. There are also many types of alcohols such as methanol and ethanol that can be produced using HAS technology. The syngas produced from gasification process will be catalytically converted to alcohols under this technology. Ethanol is an important renewable liquid fuel for motor vehicles. The production of ethanol from biomass can significantly reduce both the dependency on fossil fuel sources and environmental pollution [6].

Oil palm (Elaeis guianensis) originally originates from West Africa. It grows well in wet and humid places like Malaysia. In the present time Malaysia is the world's largest producer and exporter of palm oil. Its currently accounts for 51% of the world palm oil production and 62% of the world exports. Palm oil production in Malaysia has increased from 2.57 million metric tons in 1980 to 17.8 million metric tons in 2009 [7]. Beside palm oil availability, Malaysian palm oil also generates huge quantity of oil palm biomass including oil palm trunks, oil palm fronds, empty fruit bunches (EFB), shells and fibers in the production of palm oil. There was annual generation of 9.66, 5.20 and 17.08 million tons for fiber, shell and empty fruit bunches respectively [8]. Oil palm is a multipurpose plantation and also a prolific producer of biomass as raw materials for value-added industries [9]. For example, fresh fruit bunch contains only 21% palm oil, while the rest 6–7% palm kernel, 14–15% fiber, 6–7% shell and 23% empty fruit bunch (EFB) are left as biomass [10].

In Malaysia, there has been a strong interest in the utilization of oil palm biomass for the production of environmental friendly biofuels. The implementation of biofuels program in Malaysia is in line with the government policy in ensuring a sustainable development of the energy sector as well as promoting a clean environment. For examples, the government has embarked on the growth of renewable energy as the fifth fuel after oil, gas, hydro, and coal, initiated earlier under the Third Outline Perspective Plan (OPP3), 2000–2010 [11], and the ninth Malaysian plan (9MP), 2006–2010 [12].

Till now, a lot of work has been done and many processes are being investigated on hydrogen-rich gas production from biomasses [13–18]. Among them, thermo-chemical processes (gasification and pyrolysis) are the most promising and applied solutions for "second generation fuels".

Presently, many research works related to the gasification of biomass using different operating processes such as types of gasifiers (fixed bed, moving bed and fluidized bed), gasification agents (air, oxygen, steam or their mixtures) and operating conditions (temperature, pressure, equivalent ratio (ER)) have been presented and extensive researches have been conducted on small and medium size air gasifiers to produce low BTU fuel gas and power [19–26].

Gasifying agent is one of the most important parameters in the gasification process. It plays an important role during the gasification reactions. The agent can be air, pure oxygen, steam or their mixtures. Air is cheap and widely used in the gasification process, however, it contains large amount of nitrogen, which reduces the heating value of the syngas produced. On the other hand, if pure oxygen is used, the heating value of syngas will increase but at the same time, the operating costs will also increase due to the oxygen production [27], and the same can be said for using steam as gasifying agent. The low calorific value syngas produced from air gasification can be directly utilized as fuel for gas turbines and gas engines [28] or can used as an industrial feedstock for heat and power generation. Yet, the condensable organic compounds (tar) need to be removed using hot gas cleaning method or catalytic reforming of tar.

Currently, oil palm biomass (shell, fiber and EFB) can be converted to the high-value products via thermo-chemical conversion processes. Yang et al. [21] have investigated the use of the palm oil wastes as a feedstock to produce hydrogen-rich gas via pyrolysis process in fixed bed reactor. The authors reported that the palm oil wastes could be ideal biomass sources for biofuels production The total gas yield was enhanced by increasing reactor temperature with the maximum ~70 wt.% of gas yield achieved per raw biomass sample with good portions of H_2 (33.49 vol.%). Kelly-Yong et al. [29] have studied the thermodynamic analysis of hydrogen production from oil palm biomass in gasification reaction using supercritical water (SCW) technology. The authors reported that the utilization of SCW medium in biomass gasification can directly deal with high moisture content of biomass (>50%). Therefore, preliminary treatment such as biomass drying could be avoided which will automatically reduce the operating cost of the process. In addition, the feasibility study of obtaining hydrogen from palm oil biomass (0.117 kg H_2 kg^{-1} biomass) was obtained. Abdullah et al. [30] investigated the fast pyrolysis of EFB using 150 g/h fluidized-bed reactor to produce bio-oil. The results showed that the maximum bio-oil production was 55.1 wt.% at 450 °C at only 1.03 s vapor residence time.

This study focuses on using EFB, a waste from the palm oil industry as a feedstock material using air gasification process in bench scale fluidized bed gasifier. Different operation conditions namely reactor temperature, feedstock particle size and equivalence ratio will be investigated to achieve an improved performance of EFB conversion to energy with a high yield of hydrogen-rich gas.

2. Materials and methods

2.1. Feedstock preparation and properties

The EFB sample investigated in this study was collected from Seri Ulu Langat palm oil mill, Dengkil, Selangor. EFB used in this work is the biomass remaining as a by-product of industrial process after removal of the nuts. Samples received were relatively dry having less than 10 wt.% moisture, and were in the form of whole bunches. Particle size reduction was required to allow gasification of the EFB on the available 600 g/h reactor. The bunches were first manually chopped into small pieces that could be fed in a shredder. After that, a Fritsch grinder with a screen size of 1.0 mm was used to obtain the feedstock size of less than 1.0 mm. The distribution of feed particle size after grinding is given in Table 1. After extensive feeding trials, it is found that only particles between 0.3 and 1.0 mm were easily fed. Both the size fraction below and above this range frequently led to blockage of the available feeder.

The proximate and elemental analyses were carried out in a TGA (Mettler-Toledo TGA/SDTA 851) and CHNS/O analyzer (LECO CHNS932), respectively. The results are listed in Table 2. EFB had a very high volatile content (>80 wt.%) and low amounts of fixed carbon (<10 wt.%). The calorific value of EFB (~17 MJ/kg) was measured in a bomb calorimeter (Parr 1341); this is lower than that of coal, possibly due to the low fixed carbon and high oxygen contents in the EFB [31]. The ultimate analysis indicates that EFB is

Table 1
Particle size distribution of EFB.

Feed particle size (mm)	Mass fraction
Less than 0.3	22
0.3–0.5	50
0.5–1.0	28