Air gasification of palm empty fruit bunch in a fluidized bed gasifier using various bed materials

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Abstract: Use of lignocellulosic biomass as an alternative, renewable and sustainable source of energy has fulfilled part of the growing demand for energy in developed countries. Amongst various technologies applied to convert biomass wastes to biofuel and bioenergy, biomass gasification has attracted considerable attention. In this work, gasification of palm empty fruit bunch as a potential lignocellulosic waste was investigated in a pilot scale air-blown fluidized bed. Silica sand and dolomite were used as bed material. The bed temperature was varied in the range of 650 to 1050 ^oC. The quality of the producer gas (H_2, CO, CO_2 and CH_4) and gasification performance was assessed in terms of heating value, carbon conversion efficiency, dry gas yield and cold gas efficiency. It was concluded that high temperatures improved the quality of producer gas; maximum heating value of 5.3 and 5.5 MJ/Nm^3 were achieved using silica sand and dolomite. Maximum dry gas yield of 1.84 and 1.79 (Nm^3gas/kg biomass), carbon conversion of 91 and 85% and cold gas efficiency of 69 and 65% were obtained for silica sand and dolomite, respectively. Although the quality of the produced gas was considerably improved at high temperatures, however formation of the bed agglomerates was the major concern at temperatures above 800 and 850 ^oC for silica sand and sawdust.

Keywords: *Biomass gasification, Fluidized bed, Gas producer, Palm empty fruit bunch*

1. Introduction

In recent years, rapid development of modern industry has greatly increased the demand for energy. Today, fossil fuels are the most common energy sources in the world. Most countries which use such conventional fuels are facing major air pollution problems as it has been estimated that the world's oil reserves will get depleted by 2050 [1]. Besides, significant amount of pollutants including CO_2, NO_x and SO_x are emitted from fossil fuels into the atmosphere. Meanwhile, the cost of fossil fuel is globally increasing [1, 2]. Considering theses issues, boosts the importance of finding and exploring alternative, renewable and sustainable energy resources.

Lignocellulosic biomass is one of the potential renewable energy resources which is receiving great worldwide attentions. Malaysia as the largest producer of palm oil generates a large amount of lignocellulosic residues including palm empty fruit bunch (EFB), palm shell and mesocarp [3]. These lignocellulosic biomass feedstocks can be efficiently utilized in various thermo-chemical conversion processes to yield energy and fuels. Among various biomass conversion technologies, special attention has been paid to biomass gasification due to its high conversion efficiency [4-6].

A survey of literature reveals successful application of lignocellulosic biomass in various types of gasifiers including fixed beds [7], entrained flow [8] and fluidized beds [9-13]. However, amongst different categories of gasifiers, fluidized beds have offered advantages such as efficient mixing of gas and solid, improved reaction rate and conversion, and low tar content of the producer gas. Various gasifying agents including air, steam, oxygen-steam, air-steam, O_2-enriched air and oxygen-air-steam have been utilized in fluidized beds [6, 8, 14, 15]. Although a very high quality producer gas is not attainable through air gasification, however is boosts the feasibility of the biomass gasification for industrial application.

Although various biomass feedstocks have been gasified in fluidized beds, little data has been published on g asification of EFB in catalytic fluidized beds. Current research aims to investigate the gasification of EFB in a pilot-scale air blown bubbling fluidized bed. Calcined dolomite and silica sand were used as bed material and their effect on the quality of the producer gas was investigated.

2. Methodology

2.1. Biomass feedstock and its characterization

The biomass used in the current study was palm empty fruit bunch which was obtained from a local palm oil mill factory. The raw feed containing high amount of moisture was air dried for 2 days. The dried feed was then crashed and ground to the fibers with the mean length of 2-6 mm.

Ultimate and proximate analysis was conducted on a sample of EFB to determine the elemental composition of the biomass. The heating value of EFB was measured by a bomb calorimeter. The obtained results and data analysis are presented in Table 1.

Table 1. Ultimate and proximate analysis of EFB

Ultimate analysis (wt %)	
Carbon	43.52
Hydrogen	5.72
Oxygen	48.90
Nitrogen	1.20
Sulfur	0.66
Proximate analysis (wt %)	
Moisture	7.80
Volatiles	79.34
Ash	4.50
Fixed carbon	8.36
HHV, MJ/kg (dry basis)	15.22

2.2. System description and operation

An air blown bubbling fluidized bed gasifier with the height of 1050 mm and internal diameter of 150 mm was operated for EFB gasification. Air was introduced into the gasifier using a 0.75kW blower. Silica sand and calcined dolomite with mean size of 600 μm were used as bed material. The biomass was continuously fed into the reactor through a screw feeder conveyer equipped with an inverter. The temperature of different operating zones of the gasifier was monitored by several type K thermocouples. The operated experimental setup is represented in Fig. 1.

At start up, the system was heated up to the desired temperature of 500 °C. There was a heating chamber supplied by LPG below the distributer plate to provide the necessary heat. As the temperature of reactor reached to 500 °C, air was introduced and the biomass feeding was started. To avoid the pyrolysis of biomass inside the screw feeder, there was a cooling jacket surrounding the conveyor and cooling water always passed during the process.

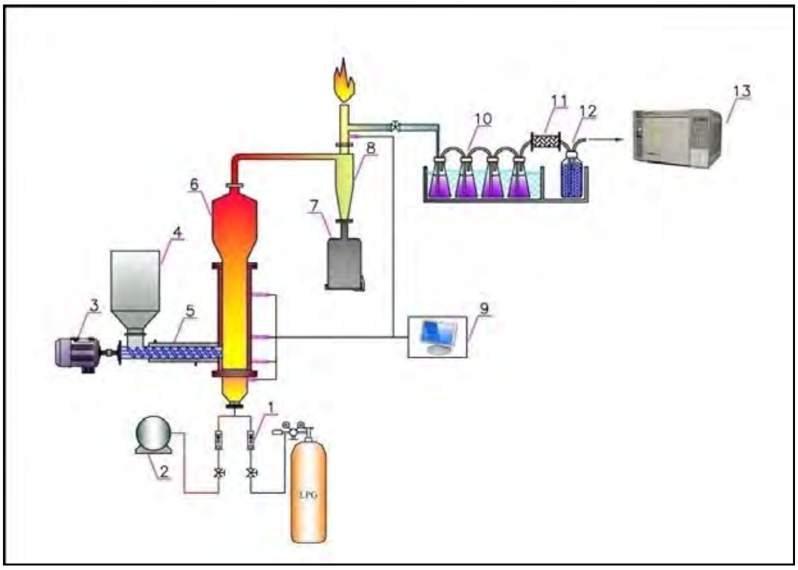


Fig. 1. Schematic representation of the pilot-scale BFB gasifier:
1. Mass flow controller; 2. Blower; 3. Variable frequency driver; 4. Feeding hopper; 5. Water cooled screw feeding system; 6. Fluidized bed reactor; 7. Particle holder; 8. Cyclone; 9. Temperature monitoring unit; 10. Condensers; 11. Fiber filter; 12. Silica gel; 13. Gas chromatograph

2.3. Gas sampling and analysis

The gasifier was operated at atmospheric pressure. The gasifier was equipped with a cyclone and the dirty outlet gas containing ash, char, tar and dust particles entered the cyclone separator. The cyclone removed ash and chars from the hot gas and derived them into the bin connected to the cyclone. Producer gas was exited from the cyclone to the incinerating device while a part of it was sent to the gas sampling unit. The gas samples were collected in several gas sampling Tedlar bags for further analysis using Gas Chromatograph (GC). The GC (Agilent Technology, 4890) was equipped with a thermal conductivity detector (TCD). A packed Carboxene 1000 (Supelco, USA) column (15 ft × 1/8 in, 80/100 mesh) was used to measure the mole fraction of permanent gases. External standard method obtained from 6 tanks of simulation gas was used to calculate the composition of the producer gas. Temperature programmed GC analysis was carried out with initial oven temperature set at 35 °C, then it was gradually increased to 210 °C at a rate of 20 °C/min. The injector and detector temperatures were 150 and 220 °C, respectively. Helium was applied as carrier gas at a rate of 35 ml/min.

3. Results and Discussions

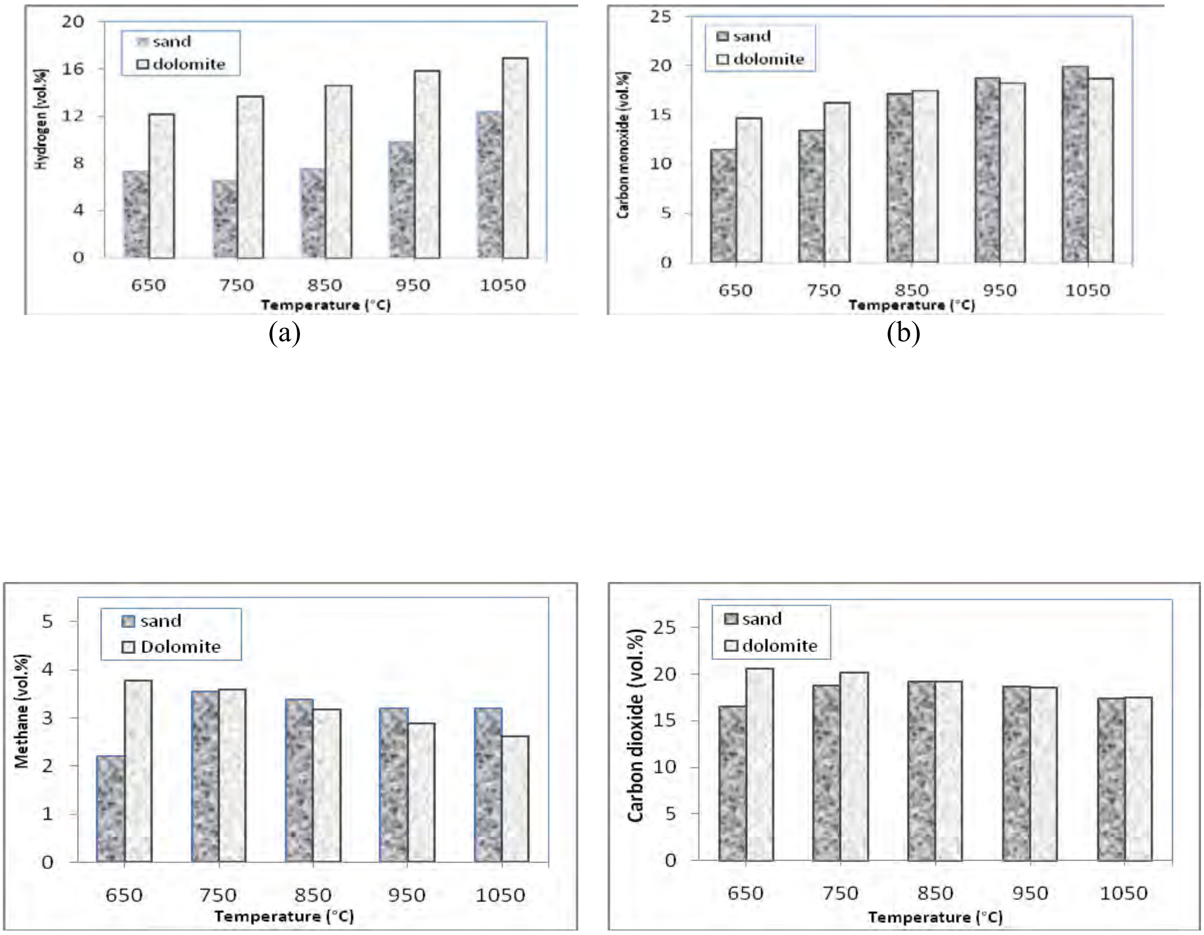
3.1. Producer gas composition

In order to investigate the effect of temperature and bed material on the composition of producer gas, the bed temperature was varied in the range of 650 to1050 ^{o}C. The results are depicted in Fig. 2 (a) to (d). As observed in Fig. 2 (a) increasing the bed temperature from 650 to 1050 ^{o}C improved the H_2 content of the producer gas from 7.3 to 12.4% and 11.1 to 16.8% for silica sand and dolomite, respectively. Such increase in the H_2 level of the producer gas was due to the improvement of the endothermic reactions (1-3) involved in the gasification process:

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ $\Delta H = +206$ kJ/mol (1)

$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$ $\Delta H = +165$ kJ/mol (2)

$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ $\Delta H = +247$ kJ/mol (3)



(a) (b) (c) (d)

Fig 2. Effect of bed temperature and bed material on producer gas composition

Beside the contribution of the endothermic reforming reactions in increasing the H_2 concentration, the remarkable higher H_2 concentration obtained using dolomite in comparison to sand was confidently related to the improved tar cracking reactions (4-6):

C_nH_m (tar) + $nH_2O \leftrightarrow (n + m/2) H_2 + nCO$ $\Delta H > 0$ (4)

C_nH_m (tar) + $nCO_2 \leftrightarrow (m/2) H_2 + 2nCO$ $\Delta H > 0$ (5)

C_nH_m (tar) $\leftrightarrow (m/2) H_2 + nC$ $\Delta H > 0$ (6)

The variation of CO level of the producer gas with respect to the bed temperature is presented in Fig. 2 (b). The obtained result revealed the positive effect of the bed temperature on CO content. As the bed temperature was raised from 650 to 1050 ^oC, the CO level increased from 11.5 to 19.8% and 16.2 to 18.7 for silica sand and dolomite, respectively. It was inferred that improved char gasification reactions (7 and 8) as well as methane reforming reactions (1-3) were the main cause of such increase at high temperatures [12]:

$C + H_2O \leftrightarrow CO + H_2$ $\Delta H= +131$ kJ/mol (7)

$C + CO_2 \leftrightarrow 2CO$ $\Delta H= +172$ kJ/mol (8)

Fig. 2 (C) shows the CH_4 level of the producer gas at various applied bed temperatures. The maximum CH_4 level of 3.8 and 3.6% was obtained at 750 ^oC for silica sand and 650 ^oC for dolomite, respectively. The results showed that the CH_4 content of the producer gas follows a reducing trend for both silica sand and dolomite at high gasification temperatures. High temperature favors endothermic methane reforming reactions, thus reducing the CH_4 content of the producer gas.

The variation of CO_2 level of the producer gas with respect to the bed temperature is presented in Fig. 2 (d).The high concentration of CO_2 was observed at low temperatures and then a drastic decrease at temperatures above 850 ^oC was experienced for both sand and dolomite. At low temperatures, CO_2 is produced through water-gas shift reaction (9) but high temperature promoted its evolution via methane reforming (2). However, the generated CO_2 was consumed through methane dry reforming (3), tar cracking (5) and Boudouard reaction (8) to yield more H_2 and CO and lead to a decrease in CO_2 level at temperatures above 850 ^oC. The lowest CO_2 content of 17.4 was achieved at 1050 ^oC for both sand and dolomite.

$CO + H_2O \leftrightarrow CO_2 + H_2$ $\Delta H= - 41.98$ kJ/mol (9)

3.2. Gasification performance

Fig. 3 (a) illustrates the effect of bed temperature on high heating value (HHV) of the producer gas for sand and dolomite. As explained earlier, high temperatures enhanced the evolution of combustible gases especially H_2 and CO which in turn resulted in an increase in HHV of the producer gas. The HHV of the producer gas increased from 3.3 to 5.3 MJ/Nm^3 and 4.9 to 5.5 MJ/Nm^3 for silica sand and dolomite, as the bed temperature was increased from 650 to 1050 ^oC.

Variations of dry gas yield with respect to bed temperature are shown in Fig. 3 (b) for silica sand and dolomite. Increase of the bed temperature improved the dry gas yield from 1.3 to 1.8 Nm^3/kg and 1.5 to 1.8 Nm^3/kg for dolomite, respectively. Increase in dry gas yield may be originated from the promotion of initial pyrolysis rate at high temperatures which increased the gas production as well as steam cracking and reforming of tars at high temperatures. In addition, endothermic reactions of char gasification at elevated temperature (7 and 8) improved the dry gas yield [11].

The result of carbon conversion calculation is presented in Fig. 3(c) for sand and dolomite. As expected, high temperatures enhanced carbon conversion efficiency due to the improvement of water-gas and Boudouard reactions (7 and 8) through which more carbon is converted to gaseous products. However, increase of the bed temperature beyond to 850 ^{o}C did not enhance carbon conversion due to the reduction of CO_2 content despite CO production.

Improvement of cold gas efficiency with increasing the bed temperature for EFB and sawdust is depicted in Fig. 4 (d). The highest cold gas efficiency of 69 and 65% was achieved at 1050 ^{o}C for sand and dolomite due to the high dry gas yield and heating value.

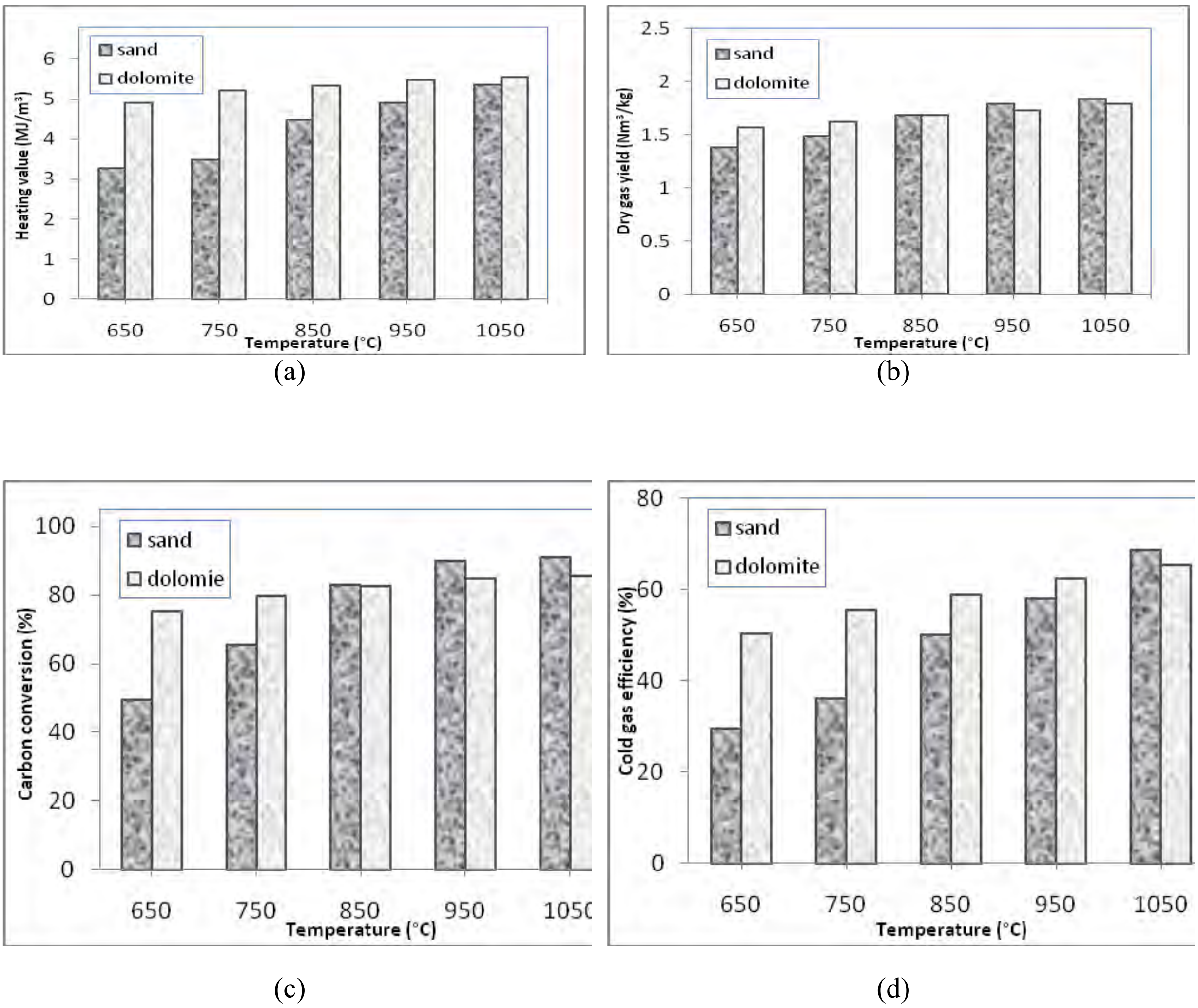


Fig 3. Effect of bed temperature and bed material on gasification performance

Agglomeration of the bed material was observed as the major concern in EFB fluidized bed gasification, especially at high temperatures. Such undesired phenomenon originated from the high K_2O content of EFB (44%) which deteriorates the sintering and agglomeration tendency of the bed materials to form low melting eutectics [16]. Increase of the bed temperature beyond to 800 and 850 °C for silica sand and dolomite, resulted in the growth of bed particle. However, agglomeration with dolomite was not severe and the size of agglomerates was not considerable in comparison to silica sand agglomerates.

4. Conclusions

Gasification of EFB as an abundant lignocellulosic waste was studied in an air blown pilot-scale bubbling fluidized bed gasifier. The effect of bed temperature and catalytic bed material on the quality of the producer gas was assessed. The achieved results proved the potential of this biomass to generate energy as the HHV of 5.5 M J/Nm^3 was obtained with dolomite. However, the agglomeration evolved at high temperatures was the main concern in EFB gasification. Thus, the EFB gasification experiments should be performed at temperatures below 850 °C to ensure the avoidance of any agglomeration.

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