Study of Performance of an Atmospheric Bubbling Fluidized Bed Combustor Using Palm Kernel Shell

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Abstract
An experimental investigation was made to study the performance of an atmospheric bubbling fluidized bed combustor using palm kernel shell (PKS) as fuel. The combustion chamber is a steel cylinder with 145mm internal diameter and 2400mm height. During the combustion test, the fuel was burnt at 7.32kg/hr and 9.96kg/hr fuel feed rates while ranging excess air from 20% to 100% for each combustor load. Tests results showed that for the fuel feed rates of 7.32kg/hr and 9.96kg/hr, maximum combustion efficiencies of 98.7% and 97.3% respectively at 80% excess air were attained. This is an improvement of 6.23% over the 92.47% limit previously established in the literature. The major gaseous (CO and NOx) emissions were at levels which were less than the U.K. environmental emission limits permitted for new fluidized bed combustor of biomass fuels. The results showed that PKS waste obtained from Nigeria can be successfully burnt in bubbling fluidized bed combustor. The combuster can thus be used for steam generation or other applications at very high combustion efficiency while maintaining low level of the major gaseous emissions.

Keywords: combustion efficiency, fluidized bed combustor, emissions, excess air, palm kernel shell

INTRODUCTION
Palm oil industry is one of the major agro-industries in Nigeria. Nigeria is currently the third largest producer of palm oil in the world after Indonesia and Malaysia with an annual production volume of 1.28 million metric tonnes (Eshalomi, 2012). During palm oil processing, a significant amount of solid wastes such as empty fruit bunches, palm press fibre and palm kernel shell (PKS) are produced. A typical fresh palm fruit bunch can produce about 5 – 7% PKS (Okoroigwe and Saffon, 2012). In Nigeria, virtually every part of the palm oil tree is useful in one form or the other; however, PKS is not maximally utilized. Only an insignificant portion is used for cooking or domestic processing while a vast majority are left unused and are very difficult to decompose, thereby creating environmental nuisance.

The fluidized bed combustion (FBC) technology has been proven to be one of the most effective and environmentally friendly technologies for energy conversion from biomass wastes (Natarajan et al., 1998; Madhivanan et al., 2010; Ninduangdee and Kuprianov, 2014). FBC technology offers a number of advantages compared to other combustion technologies: the possibility to use a wide variety of fuels and its environmental friendliness in terms of reduced noxious combustion products (Kuprianov and Peramchar, 2003).

Several experimental investigations have been carried out to date on fluidized bed combustion of different biomass wastes. Patumsawad (2002) examined the characteristics of palm waste when combusted in a 150mm internal diameter bubbling fluidized bed combustor. The study showed that oil palm waste could be burnt successfully in the combustor. It was discovered that the relationship between excess air and combustion efficiency is such that combustion efficiency increases with excess air; reached a maximum value for a particular feed rate, then starts to fall.

Permatasari et al. (2009) examined the combustion characteristics of palm kernel shells and palm fibers in a bubbling fluidized bed combustor. The results indicated that the axial temperature profile reduces successively along the combustor height and the combustion efficiencies gave satisfactory values. The maximum combustion efficiency for palm kernel shells was 60% and that for palm fiber was 89%.

Raji et al. (2012) examine the effect of the combustion of three different sizes of palm kernel shells on temperature profile and emission characteristics in a 150mm internal diameter experimental bubbling fluidized bed combustor. The results showed that efficient and environmentally friendly combustion of palm kernel shells could be achieved in a bubbling fluidized bed combustor and that fuel particle size could have a pronounced effect on the bed temperature and combustion characteristics. Many of these investigations focus only on obtaining high combustion efficiency at low emissions. However, the fluidized bed combustor can be used for steam generation or other applications at very high combustion efficiency while maintaining
low level of emissions. The objective of this work is to determine the effect of excess air and fuel feed rates on the temperature distribution in the fluidized bed combustor and on the major gaseous (CO and NO) emissions from the combustor as well as determine the combustion efficiency and the rate of steam generated.

MATERIALS AND METHOD

The apparatus used for the present work was an atmospheric bubbling fluidized bed combustor which was designed and constructed in the Faculty of Engineering and Technology workshop of the Ambrose Ali University, Ekpoma, Nigeria. A schematic diagram of the fluidized bed combustor is shown in Fig. 1. The combustor is a steel cylinder with 145mm internal diameter and 2400mm height. The combustor was covered with refractory castable insulation to minimize the heat loss during the combustion process. Air enters the combustor from the plenum chamber just below the combustor through a nozzle type distributor plate. The air acts as both the fluidizing air and the primary combustion air. The air distributor plate has 19 nozzles and each nozzle has twenty seven 1.5mm diameter orifices drilled radially through it. The arrangement of the nozzles is to ensure a uniform distribution of air flow over the entire bed at quite low pressure drop across the distributor plate. The lateral orifices prevent flow of solid particles into the nozzle and the plenum chamber. Air velocity were adjusted manually and measured by pitot-tube connected to differential digital manometer.

River sand of 0.486mm mean particle size was used as the inert bed material. In the bed section, a copper coil heat exchanger was wound around the stainless steel pipe to control the bed temperature by circulating cooling water through the coil. The bed temperature was regulated to the desired temperature (800°C) by adjusting the flow rate of the cooling water. This was to prevent bed agglomeration and formation of oxides of Nitrogen through the thermal-NOx formation mechanism.

Start-up of combustion in the bed was initiated by gradually opening the valve on the propane gas-line, thereby allowing the propane gas flow into the combustor to mix with the primary air entering the combustor from the orifices. The mixture was then ignited. The propane gas was used as an auxiliary fuel to raise the bed temperature to a designated temperature (600°C), normally above the ignition temperature of the fuel. During combustion of the fuel, the bottom ash flows into an over-flow pipe while the fly-ash and other solid particles are separated from the flue gases by a cyclone separator located at the combustor exit.

To measure the temperature variations inside the combustor, Ni/Cr – Ni thermocouples (TC), type K with a resolution of 1°C was used. The thermocouple probes were inserted into the combustor at eight different heights of 150mm, 250mm, 350mm, 450mm, 800mm, 1200mm, 1600mm and 2000mm above the distributor plates and all sealed with exhaust repair putty. Similar thermocouples were used to measure the water inlet and steam outlet temperatures. The thermocouple probes were each connected to digital display units. Measuring cylinder (together with a stop watch) was used to measure the volume flow rate of water. A pressure gauge was placed on the steam outlet pipe to measure the steam pressure. The CO and NO emissions from the exhaust pipe were measured using an SV – 5Q Automobile Exhaust Gas Analyzer. The probe of the exhaust gas analyzer was inserted firmly in a hole drilled in the exhaust pipe. Measurement of the pressure drop across the bed was done using a differential digital manometer which has a range of 0 to 7000mbar with a resolution of 5mbar.
The combustion efficiencies were calculated according to the procedure developed by Saxena et al. (1991) and Saxena and Jotshi (1994) based on the knowledge of the compositions of the fuel and flue gases as well as the fractional excess air supplied using the relation

\[
\eta_{e} = \left( \frac{Q_f - Q_L}{Q_f} \right) \times 100 \%
\]

where \( Q_f \) is the higher heating value of fuel, \( Q_L \) is the total heat losses due to unburnt carbon and incomplete combustion of carbon monoxide.

The rate of steam generated, \( Q_{\text{wet}} \) was calculated using the formula

\[
Q_{\text{wet}} = \dot{m}_w (H_{w2} - H_{w1}) \]

where \( \dot{m}_w \) is the mass flow rate of water/steam, \( H_{w1} \) is the enthalpy of water at inlet, \( H_{w2} \) is the enthalpy of steam at outlet temperature and pressure.

**Experimental Procedure**

The PKS fuel was gradually fed into the combustor through the hopper. The fuel feed rates were in-turn adjusted to a minimum value of 7.32kg/hr and a maximum value of 9.96kg/hr respectively. The ratio of primary to secondary air was fixed at 70:30. The primary and secondary air velocities were adjusted to 20% excess air for each fuel feed rate. In addition, the water flow rate was adjusted such that the bed temperature remains steady at 800°C. The conditions within the combustor were allowed to stabilize for about 5 minutes and thereafter readings were taken. These procedures were repeated for 35%, 50%, 65%, 80% and 100% excess air respectively.

**PKS and Sand Characteristics**

The PKS wastes was collected from local mills, sorted and crushed. The proximate and ultimate analyses of PKS are shown in Table 1. The mean particle size of sand and the PKS fuel were determined by a sieve shaker with different sieve sizes. The bulk density, true density and static voidage of the PKS and sand were also determined and the results are shown in Table 2.

**RESULTS AND DISCUSSION**

**Temperature Distribution**

The temperature distribution along the combuster axial height was plotted against the various percentage excess air values as shown in fig 2 to fig 4.

![Fig. 2. Temperature distribution along combuster axial height for fuel feed rate of 7.32kg/hr](image1)

![Fig. 3. Temperature distribution along combuster axial height for fuel feed rate of 9.96kg/hr](image2)

![Fig. 4. Comparison of the temperature distribution along the combuster axial height at 80% excess air for fuel feed rates of 7.32kg/hr and 9.96kg/hr](image3)
As the PKS is fed into the combustor, the fuel particles get heated quickly because of the high heat transfer from the bed and intensive mixing of bed material. This releases an enormous quantity of volatile matter. A high proportion of the volatiles bypass the bed and burn in the freeboard while a high percentage of the high carbon content char left after the devolatilization, is burnt in the bed. The bed temperature was fairly constant for the various excess air values as shown in fig. 2 and fig. 3. However, in the freeboard at a height of 450mm, the axial temperature decreases slightly. Furthermore, at a height of 800mm, the axial temperature did not record an increase but it exhibited a further drop. The reason for this is that secondary air enters the combustor at a height of 500mm. Because the secondary air was not preheated, it needs energy to attain the combustor temperature. This trend is in agreement with that of Okasha (2007).

Thereafter, the axial temperature began to increase. At each of the fuel feed rates, increasing the excess air values (i.e. increasing the combustion air velocities), increases the axial temperatures at all the locations in the freeboard. The reason for this is that low excess air values (i.e. low air combustion velocities), results in inadequate mixing. Increasing the excess air values, increases the turbulence in the combustor, resulting in an improve fuel mixing and air-fuel contact and so the quantity of volatiles in the freeboard is burnt at a higher rate. A further increase in the excess air values causes a strong combustion zone to move to the top of the freeboard and losses in unburnt fuel particles increases. For all the fuels and at all percentage excess air values, maximum temperature was obtained at a height of about 1200mm and a gradual drop in temperature was observed.

For higher combustion efficiency to be achieved, the combustion air was split into primary and secondary combustion air. The primary combustion air was supplied through the distributor plate at a slightly higher rate than that needed for char combustion while the remaining combustion air was supplied in the freeboard as secondary air. Because the secondary combustion air was supplied in the freeboard, a considerable increase in the axial temperature in the freeboard was observed as shown in fig. 2 and fig. 3. This shows that combustion can be improved by air staging.

Increasing the fuel feed rates from 7.32kg/hr to 9.96kg/hr for similar excess air values results in higher freeboard temperatures for all the locations as shown in fig.4 for 80% excess air. This could be explained by the fact that higher feed rates imply higher volatiles combustion in the freeboard.

Rate of Steam Generated

The plots of the rate of steam generated versus percentage excess air values for fuel feed rates 7.32kg/hr and 9.96kg/hr is shown in fig. 5.

It was observed from fig. 5 that the rate of steam generated (which is the same as rate of heat removed from the bed by the water/steam in the copper coil) reduces as the percentage excess air increases. The reason for this is that as the excess air increases, the rate of heat removed from the bed to the freeboard by the excess air increases. This leads to a reduction in the rate of heat removed from the bed by the water/steam in the copper coil and hence a reduction in the rate of steam generated.

The maximum rate of heat removed from the bed by the water/steam in the copper coil was 13.55kW at fuel feed rate of 9.96kg/hr. This was low, however, due to the high freeboard temperature, higher quantity of heat can be removed in the combustor by proper design and positioning of the heat transfer tube.

Flue Gas Emissions

The CO and NO emissions at 6% O2 in the flue gases were plotted respectively against the percentage excess as shown in fig 6 and fig 7.

As shown in fig 6, CO emissions decreases as percentage excess air increases. This decrease in CO emission may be attributed to the high turbulence produced by the supply of secondary combustion air in the freeboard which resulted in improved combustion of volatile matter. This result follows similar pattern with those of Raji et al. (2012) and Ninduangdee and Kuprianov (2014). At the optimum excess air, the CO emissions at 6% O2 in the flue gases were 9ppm and 21ppm for fuel feed rates of 7.32kg/hr and 9.96kg/hr respectively.

As shown in fig 7, the NO emissions were found to increase with increase in excess air. This was due to
that fact that as the excess air increase, more oxygen in the air reacts with more nitrogen in the fuels. This result follows also similar pattern with those of Raji et al. (2012) and Ninduangdee and Kuprianov (2014). The maximum values of NO emissions at 6% O$_2$ in the flue gases were 104.81ppm and 133.61ppm for fuel feed rates of 7.32kg/hr and 9.96kg/hr respectively. However, the generally low values of the NO emissions were as a result of the fuel-NO formation mechanism.

At the optimum excess air, the major emissions were less than the U.K. environmental emission limits permitted for new fluidized bed combustor of biomass (Environment Agency, 2002) which is 120.1 ppm (150mg/m$^3$) for CO and 186.8 ppm (250mg/m$^3$) for NO at 6% O$_2$ in flue gases.

![Fig. 6 CO emissions at 6% O$_2$ in flue gases](image)

![Fig. 7 NO emissions at 6% O$_2$ in flue gases](image)

**Combustion Efficiency**

The combustion efficiency was plotted against the percentage excess air for each of the biomass fuels combustion as shown in fig 8. The highest combustion efficiencies of 98.7% and 97.3% at fuel feed rates of 7.32kg/hr and 9.96kg/hr occurs at 80% excess air. This means the combustion efficiency increases with increase in excess air up to a maximum and then begins to decline. In other words, the quantity of unburnt carbon reduces with increase in excess air. The reasons for this is that increasing the amount of excess air, increases the quantity of oxygen needed for combustion and the turbulence in the combustor, thereby leading to an increase in the combustion efficiency. This result shows the same trend with that of Patumsawad (2002). However, any further increase in the percentage excess air above the optimum value of 80% decreases the combustion efficiency. The reason for this is that increasing the percentage excess air above the optimum value results in higher unburnt combustible losses in the flue gases and hence lower combustion efficiency. This result agrees with that of Ninduangdee and Kuprianov (2014). They found that when the percentage excess air becomes optimum, combustion efficiency was a maximum and any additional increase in the excess air results in a decline in the combustion efficiency.

The maximum combustion efficiency of 98.7% attained for PKS combustion in this work is an improvement over the 92.47% limit previously established for PKS combustion in the literature.

![Fig. 8 Combustion efficiency various percentage excess air](image)

**CONCLUSION**

The fluidized bed combustor was successfully tested for burning PKS at fuel feed rates of 7.32kg/hr and 9.96kg/hr while varying the percentage excess air. There was a general trend of temperature distribution along the combustor axial height for all tests. The maximum combustion efficiency occurred at 80% excess air. The introduction of secondary air in the freeboard led to the rise in temperatures in the freeboard and hence improvement in combustion efficiency and reduction in CO emission. At the optimum excess air, the CO and NO$_x$ emissions were less than the U.K environmental emission limit permitted for new fluidized bed combustor of biomass: CO less than 120.1ppm and NO less than
186.8ppm at 6% $O_2$ in the flue gases. The rates of steam generated i.e. the rates of heat removed from the bed by the water/steam in the copper coil were rather low and can be improved by appropriate design and placement of the heat transfer tube(s). The use of more advanced techniques for determining the combustion efficiency is expected to produce better results.

Fluidized bed combustors can be employed for the purpose of utilizing the abundant biomass wastes available in Nigeria for steam generation or other applications.

REFERENCES


