Effects of Particle Size Variation of Palm Kernel Shell on Emission Performance and Temperature Distribution of a Bubbling Fluidized Bed Combustor

Raji Tunde Oyelade, Oyewola M. Olanrewaju, Salau T. A. O.

Abstract - The effect of particle size variation of Palm Kernel Shell (PKS) on the temperature distribution and emission performance of a bubbling fluidized bed combustor (BFBC) was examined. PKS feedstock received from the farm were classified to three different sizes; 'as received' (6-22 mm), 'mildly crushed' (2-12 mm) and 'pulverized' (<2 mm). Combustions of the fuels were performed at Excess Air (EA) of 30, 50, 80 and 100% and fuel feed rate of 5 kg/hr in all cases. An electronic based regulating unit incorporated in the BFBC ensured that the inert bed temperature (T2) is limited to a maximum value of 750±10 ^{o}C in all the experiments. Significant impact of particle size variation on emission and temperature distribution in the BFBC were observed. At all EA, intense combustion and stable inert bed temperature (T2 = 750 ± 10 ^{o}C were obtained when firing size (6 - 22 mm), conversely (<2 mm) at EA>30% showed a rapid drop of inert bed temperature from 750-500 ^{o}C. Particle size 6-12 mm and 2-12 mm gave concentrations of pollutants that were within Nigeria emission limits at CO(195-856 ppm), NOx(9-182 ppm and SOx(8-93 ppm). No evidence of ash agglomerations was observed during the investigation thereby confirmed the effectiveness of the developed BFBC.

Keywords: Experimental model BFBC; PKS; Particle size; combustion; ITRU

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1. INTRODUCTION

Availability of adequate energy is key to socio-economic development of any nation and indeed central to well-being of its citizenry; therefore adequate energy is as essential as food and water. Fossil fuel account for principal proportion of the world energy, Over 80% of world primary energy demand is still derivable from fossil fuel combustion [1]. However this could not be perpetuated indefinitely. Firstly, reserve of fossil fuel is finite; in fact, it is depleting at a rate that gives much concern and this is beyond man's control. Secondly, climate change and associated potential catastrophe exist due to accumulation in the atmosphere of CO2 and other GHG, emission of which fossil fuel combustion is principally responsible [2]; and thirdly, there is the rising cost of fossil fuel. In the near future, price will likely get higher as supply starts dwindling and demands due to modernization continue to soar. These are the key reasons that spur renewed interest in use of biomass for energy generation. Presently biomass use account for about 14% of global primary energy use [3]. This percentage however varies from as low as 3% in developed county to average of 35% in developing countries [3]. In Nigeria about 37% of primary energy use comes from biomass [4], mostly in form of domestic heat sources and small commercial processes.

Even with this magnitude of consumption, huge quantities of biomass (especially agricultural and forestry wastes) are still left unused, allowed to rot thereby generating a more potent GHG; methane. Oil Palm tree is one of the most widely cultivated agricultural plants in the world, principally as a source of edible oil. In Nigeria over 2.5.milliom hectares of land is employed for its cultivation, larger fraction of this grow in the wild [5]; a fact that may in part be responsible for the reason why significant portion of palm tree wastes are generally left unused in the farm. Investigation had shown that PKS account for about 8% of Fresh fruit brunches (FFB), therefore considering estimated cultivated land space (2.5x106 Ha), annual yield (10tonnes/hectare) [6], Heating value (16.23MJ) [7]. The aggregate energy generating potential of PKS in Nigeria may be estimated to be about 32 PJ. This undoubtedly is a huge capacity for clean energy generation if fired with appropriate combustion technology.

Fluidized bed combustion technology has been described as the most versatile technology for harnessing energy from biomass and other difficult to burn fuel with minimum emission of pollutants. Several articles on fluidized bed combustion of different biomass are in literature, treating different aspect of combustion with the aim of getting results that will be replicated in a commercial scale for efficient and environmentally friendly operation. The observed trend is that authors generally focus on biomass found within their immediate environment, for instance

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influence of secondary air injection on combustion efficiency of sawdust was examined by [8], it was found that injection of secondary air into the freeboard above the fuel bed created a more vigorous mixing of combustion air with the volatiles, abating the CO levels in the flue gas. It was observed that the enlarged freeboard zone had a considerable impact on CO reduction and invariably CE improvements. [9] Examined the characteristics of palm waste when combusted in an experimental model BFBC. The study showed that oil palm waste could be burnt successfully in a BFBC, it was also noted that EA has pronounced effect on combustion efficiency; such that CE increases with EA then starts falling after reaching a maximum value for the particular feed rate. This was explained with the fact that beyond the maximum point the EA promotes higher elutriation of unburnt fuels particle. A maximum CE of 92.47 was achieved at 50% excess air. [10] Reported that the use of air staging is beneficial to reduction of CO emission when palm waste is combusted in a BFBC, a maximum combustion efficiency of 89% was achieved. Literature had shown that utilisation of biomass as fuel for energy generation could be a challenging process since unlike fossil fuel, biomass composition varies widely. Investigations had shown that pre-treatment in terms of fuel re-sizing, drying or densification etc. may be imperative to securing a smooth operation. Pre-treatment of biomass for energy generation in commercial scale will introduce additional steps, technical complications and cost implication which could render the use of such biomass uneconomical. Recent study by Raji, Oyewola and Salau [11] had shown that 'as received' PKS obtainable from Nigeria farm may be fired directly in a BFBC to generate energy at high combustion efficiency and an acceptable level of pollutants' emission. The objective of the current study, in furtherance of what was examined by [11], is to investigate the effect of particle size variation on temperature distribution and pollutants emission from the BFBC.

2 METHODS

2.1 APPARATUS

The experimental model BFBC employed in this article has been properly described in another technical papers [12]; it consists of five 150 mm diameter stainless steel modules assembled together and partitioned into lower and upper section. Modules 1 & 2 formed the lower section while the remainder fully assembled is the upper section. See Fig. 1 and 8. The objective of the partitioning includes; enabling observation of the fluidization process and the combustion processes at start up or anytime necessary and to facilitate calibration of biomass feeder with respect to any fuel. The distributor plate, sandwiched between module 1 & 2 was fabricated from 10mm thick stainless steel plate bearing 13 standpipes. Each standpipe has forty 1.5 mm holes drilled in a definite geometric pattern around it. Silica sand mean diameter of 500 micron is employed as the inert bed material. Supply of fuels from the hopper to the inert bed is done with a conveyor-screw type biomass feeder equipped with an infinitely variable speed gear motor. The feeder discharge is located 400 mm above the distributor plate. At the junction between biomass feeding pipe and the combustor body a fluidizing air pre-heater / biomass feeding pipe's cooling attachment is provided; firstly, to minimize the biomass burning before reaching the fluidized bed and secondly, to utilize the heat energy that would otherwise be wasted and consequently cut down the fuel usage per useful energy generated. This unit is shown as G in Fig.1. The BFBC is also equipped with an inert bed temperature regulating unit (ITRU), which enable fixing of the inert bed temperature to any specific value during the experimental runs. The ITRU was designed to perform this function in either of these modes:

i. Deactivate both the biomass feeder and the centrifugal blower as soon as the pre-set T2 is achieved.

ii. Deactivate only the biomass feeder; ensure the centrifugal blower is constantly on during the experimental runs.

For consistency, mode (i) was employed in this investigation. Observation had shown that the frequency of switching off and on of the ITRU is an indication of the intensity of combustion taking place within the inert bed; the higher the intensity the higher the frequency.

2.2 THE FUEL

Palm kernel shell (PKS) is the hard, non-edible part of oil palm fruit, left to waste during oil palm processing after removal of the succulent outer layer and the oil rich endosperm. Like other biomass it is essentially made up of lignin, hemicelluloses and cellulose molecules [13].

In Nigeria the method of separating the oil rich endosperm generally leaves PKS fragments that vary in size between 6 – 22 mm. In this work this is called 'as received' PKS or Size A.

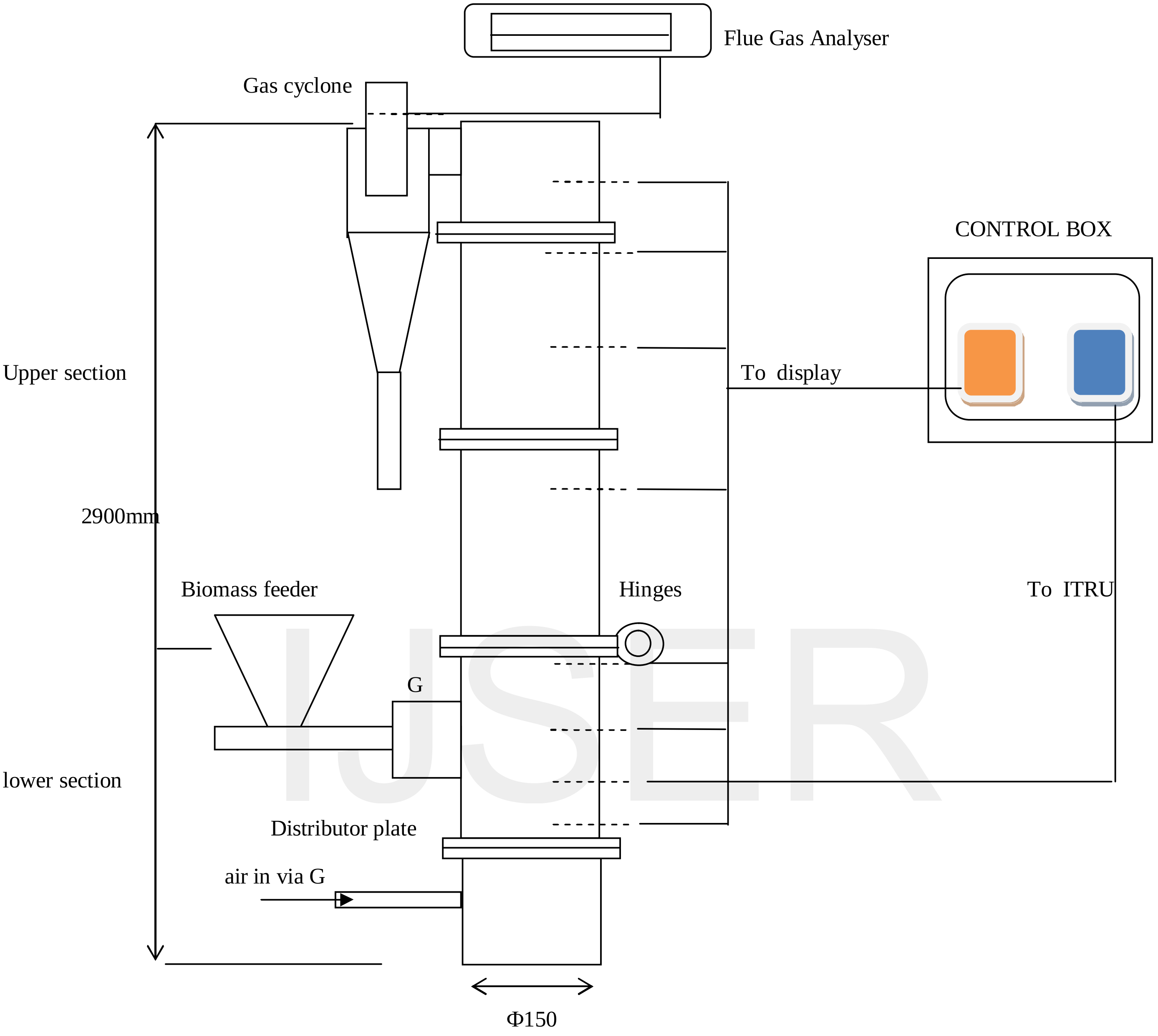
Two other sizes examined were obtained via crushing and classification by sieve to required particle size of 2 – 12 mm and < 2mm. This is also referred to as Size B and Size C respectively.

Table 1 show the proximate analysis of the PKS sample evaluated from laboratory analysis and the corresponding ultimate analysis obtained with the correlation proposed by [14] is shown on Table 2.

TABLE 1

PROXIMATE ANALYSIS (% BY MASS, AS RECEIVED)

Items	PKS (wt.% as received)
Fixed carbon	11.79
Volatile matter	79.60
Moisture	6.93
Ash	1.68



- - - - -	nine thermocouples (T1 – T9) arranged axially along the combustor body.
G	Fluidizing air pre-heater/Biomass feeding pipe's cooling attachment.

Lower section is module 1& 2

Upper section is module 3, 4& 5

Fig. 1. Schematic drawing of the developed BFBC

TABLE 2

ULTIMATE ANALYSIS AND HHV USING CORRELATION [14, 15] RESPECTIVELY (% BY MASS, AS RECEIVED)

Elements	PKS
Carbon	43.73
Hydrogen	5.55
Oxygen	41.50
Nitrogen	NIL
Sulphur	NIL
Ash	1.68
Moisture	6.93
HHV MJ/kg	16.53
LHV MJ/kg[16]	16.23

2.3 CALCULATION OF COMBUSTION EFFICIENCY

Combustion efficiency in this investigation was evaluated by estimating the heat losses due to incomplete combustion (qic) and presence of unburned carbon in the fly ash(quc) as:

$$Q = 100 - (qic+quc) \quad (1)$$

According to [17 , 18] qic, quc may be estimated as

$$qic = 126.4 \times 10-4CO(6\%O_2)\ Vdg\ /\ LHV \quad (2)$$

$$quc = 32866A.Cfa/(LHV(100 - Cfa)) \quad (3)$$

where, Vdg the theoretical (reference) volume of dry flue gas (Nm3/kg, at 0 °C and 1 atm is related to V_0 the theoretical volume of air (Nm3/kg, at 0 °C and 1 atm) required for firing 1 kg biomass fuel under stoichiometric conditions as [16 -18]:

$$Vdg(6\%) = 0.01866(C + 0.375S) + 0.79V0 + 0.008N + (\rho ref - 1)V0 \quad (4)$$

$$V0 = 0.0889(C+0.375S)+0.265H-0.0333O \quad (5)$$

Cfa , A are the unburned carbon fractions in the flue gas and the fuel ash content respectively

For the range of EA employed during this investigation the total particulates collected at the cyclone separator were insignificant, for instance total particulates collected over a period of 30 minutes when firing Size B was calculated as a mere 0.667% of the fuel input. The major proportion of this occurred at higher EA; in view of this combustion efficiency was estimated as:

$$CE = 100 - qic \quad (6)$$

2.4 EXPERIMENTATION

With the control switched on, fluidization air via the centrifugal blower was tuned to achieve a bubbling inert bed condition; at this point propane gas passed through 8 mm diameter stainless steel pipe located 10 mm above the distributor plate was switched on and ignited. The inert bed temperature (T2) was allowed to rise to 600 °C, this took about 29 minutes. Prior investigations had revealed that the more turbulent the inert bed during pre-heating the faster the specified inert bed temperature is achieved. PKS was fed in via the screw feeder. Four different experimental runs at different degree of excess air (EA) were conducted for each sizes A, B and C. The composition of the flue gas (CO, CO_2, NOx, SOx), Excess air (EA) were monitored using Bacharach PCA 3 flue gas analyser connected to a port located before cyclone separator inlet. Temperatures were taken from nine zones located along the combustor height via Type K thermocouples fitted to the first 8 zones and in-built temperature sensors of the flue gas analyser recorded the temperature in the ninth zone. The measurements accuracy of this equipment are: ±5% of reading or ± 10 ppm for CO in the range of 0-2000 ppm, ±10% for 2000-4000 ppm; ± 10% of values between 2001 to 4,000 ppm for NOx and SOx. The thermocouple for zone 2- inert bed upper region (located 20 cm above the distributor plate) was connected to the ITRU and this temperature 'T2 or Tb' in all the experimental runs was set to 750 °C. Temperature zones T1, T2, T3, T4, T5, T6, T7, T8, and T9 are located 10, 20, 35, 80, 120, 160, 200, 240 and 260 cm respectively above the distributor plate.

3 RESULTS AND DISCUSSION

3.1 Impact of EA on temperature distribution in the BFBC

For each of the fuel sizes, experimental runs were conducted at four EA (30%, 50%, 80% and 100%). Experience had shown that optimal combustion characteristics of biomass fuels usually falls within this range of EA. For example [19] noted typical excess air to achieve highest efficiency for different fuels as (5 - 10%) for natural gas, (5 - 20%) for fuel oil and (15 - 60%) for coal.

Emission values obtained were corrected to values at 6% of oxygen in the flue gas. These values were used to generate graphs against the EA (30 – 100%).

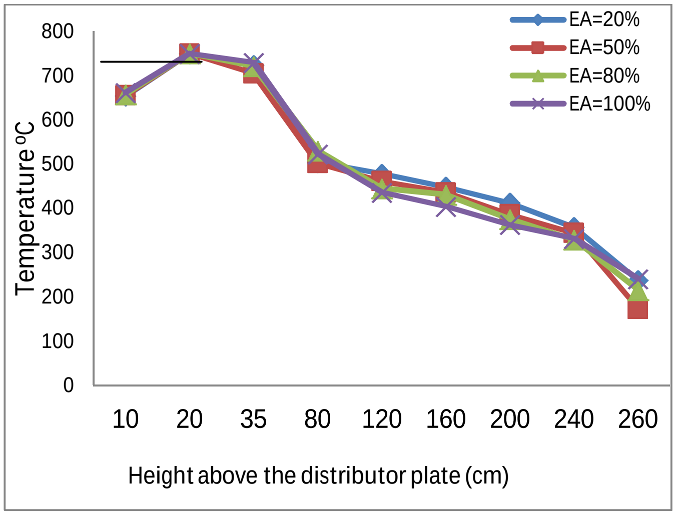


Fig. 3. Effect of EA on Temperature profile in the BFBC for combustion of ('as-received' PKS) 12 – 22mm.

Temperature profile for ‘as received’ particle size 6 – 22 mm is shown in Fig. 3. At all EA the temperature rose from the distributor plate to a maximum between 20 and 35 cm above the distributor plate; subsequently it reduced progressively to the lowest at the exhaust. The inert bed temperature T2 was noted steady at 750±10 ^{o}C in all cases. With exception of slight fluctuations at the freeboard region, thermal disparity at each zone due to EA variation was minimal. Overall, EA has weak impact on the temperature distribution in the BFBC for this size; particularly for the region below the bed splash zone (distributor plate – 80 cm above). This is confirmed in Fig. 3 as overlapped lines for the temperature in the BFBC from the distributor plate to 80 cm up. Also, it was observed that the frequency at which the ITRU activated / deactivated the biomass feeder and the centrifugal blower was higher for this particle size. The rate was highest, about 5 times per minute with EA=30%, and lowest (about 2 times per minute) with EA=101%, this signified a significant combustion intensity in the inert bed at all EA for particle size 6 – 22 mm.

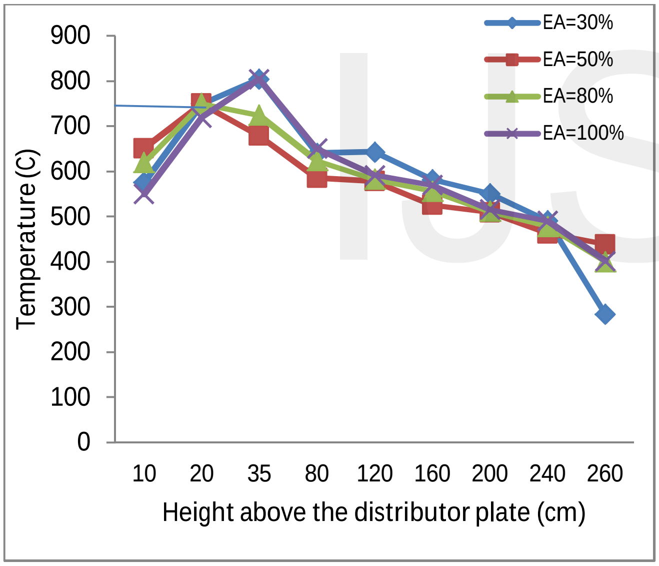


Fig. 4: Temperature profile for mildly crushed particles Size B (2-12) mm at different percentage of excess air

The temperature profile for particle size 2-12 mm (Fig. 4) indicated a combustion activity that was not as intense in comparison to the bigger particle size (6-22 mm). Though the inert bed temperature was stable at 750±10 ^{o}C for EA < 80%, at higher EA the combustion intensity reduced. For instance for EA= 100%, ITRU did not switched off and temperature T2 dropped to 720 ^{o}C where it remained constant. This indicated a lower rate of combustion within the inert bed. This result revealed that at EA=100% it might be challenging to use 2-12 mm for commercial operations if heat extraction from inert bed is necessary (e.g. via placements of tubes for flowing air or water inside the inert bed). In comparison this may not be an issue with the use particle size 6 – 22 mm.

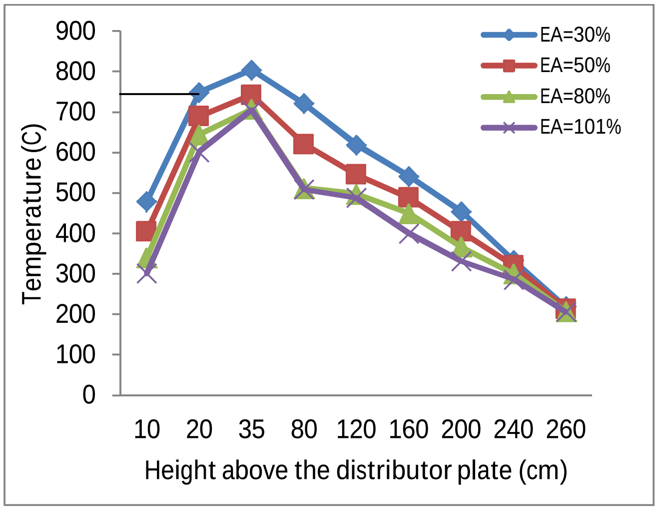


Fig. 5. Temperature profile for the pulverized PKS (<2 mm) at different percentage of EA

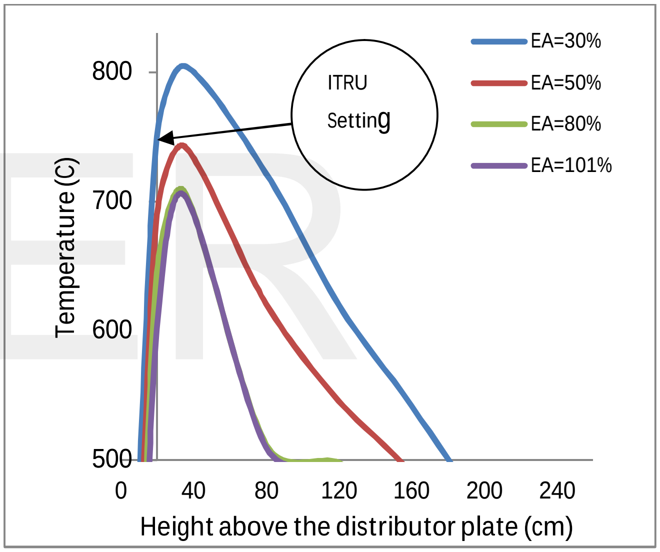


Fig. 6. A close-up view of temperature profile of pulverized <2 mm. Note that the vertical axis represents ITRU sensor location. Note that with increasing EA intersection descends.

Particle size <2 mm gave thermal characteristics that is nearly a direct opposite of ‘as received’. As shown in Fig. 5, the highest freeboard temperature (805 ^{o}C) during the investigation was observed when firing this size at EA=30%,; this is probably due to the high palm fibre contents of this particle size. At all EA the temperature T1 was low, the maximum observed value for T1 was 480 ^{o}C at EA =30%. Investigations showed that T1 and T2 decreased at a more rapid rate as EA increased for this particle size in comparison to the two bigger sizes. At EA≤ 30% the ITRU switched off / on approximately once every three minutes; this was much slower rate than observed for the bigger sizes 6-22mm and 2-12mm. This indicated that heat generation rate from combustion of < 2 mm was much lower. At EA≥30% temperatures in all the zones plummeted (See Fig. 6 for clearer view) and the investigation was stopped to re-start the BFBC via infusion of propane gas.

The poor thermal characteristics exhibited by this size are possibly due to its compositions and bulk density. PKS <2 mm is comprised of high quantities of light palm fibers and granules of PKS; the aggregate bulk density at less than 200 kg/m^3; (<< about 1000 kg/m^3 noted for particle size 2 – 12 mm). Since over-bed feeding of the fuel was employed, when EA> 30% the particles being light; a significant percentages of it are easily blown to the freeboard region. This resulted into occurrence of two actions simultaneously. Firstly, the fuel supplies to the inert bed diminished thereby caused reduced char oxidation and consequently a lower T1 and T2. In addition, out of the reduced quantities that got to the inert bed, due to the low bulk density, insignificant quantities actually penetrated the inert bed lower region therefore low T1 (300-350 ^{o}C) observed. Secondly, the particles at the freeboard region de-volatilized and burn therefore the higher freeboard temperature. At high EA, increased elutriation of the light particles resulted in fuel starvation in the inert bed which caused stoppage of the combustion process. At this point the incoming fluidization air merely fluidized and cooled the bed hence the rapid drop in temperature observed at EA=50%.

3.2 Impact of particle size on temperature distribution in the BFBC

The investigations also revealed that particle size variation have drastic effect on the temperature distribution in the BFBC. As shown in Figure 7, at EA≤30% the highest average dense phase temperature was observed for size 6 – 22 mm. The tendency to settle and burn in the lower dense phase region is higher for the big particle size whereas the medium and small particles tends to float. On the contrary higher average freeboard temperatures were obtained for the 2 smaller sizes due to the comparatively smaller mass of their individual particles. Sizes < 2 mm and 2-12 mm got easily blown to the freeboard region. Also contributed to the high freeboard temperature was massive elutriation of the char and particle by the up-flowing stream of gases. The effects of the size variation are clearly noticeable from the temperature profiles as exhibited in Fig. 7-10

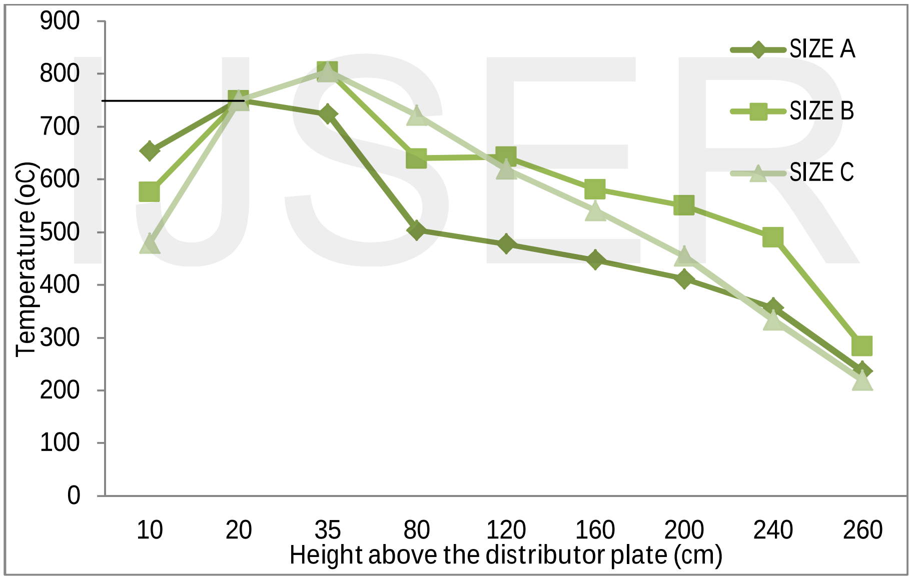


Fig. 7: A comparison of the temperature profile for all the particle size at EA=30%

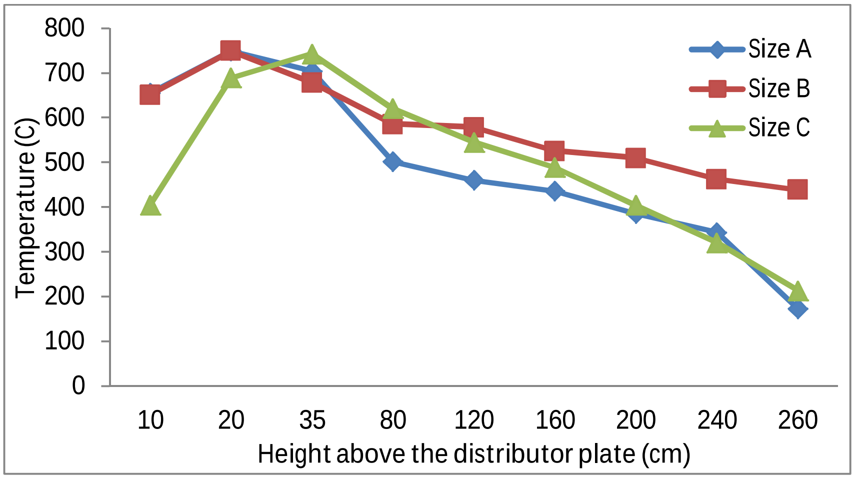


Fig. 8: A comparison of the temperature profile for the particle sizes at EA=50%

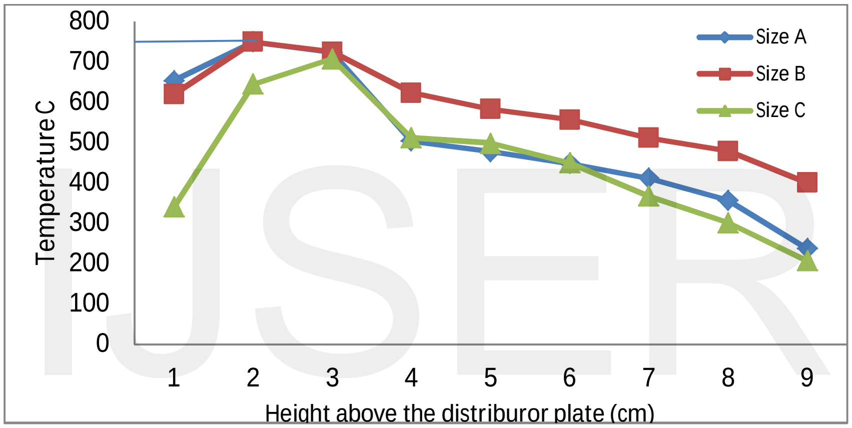


Fig. 9: A comparison of the temperature profile for the particle sizes at EA=80%

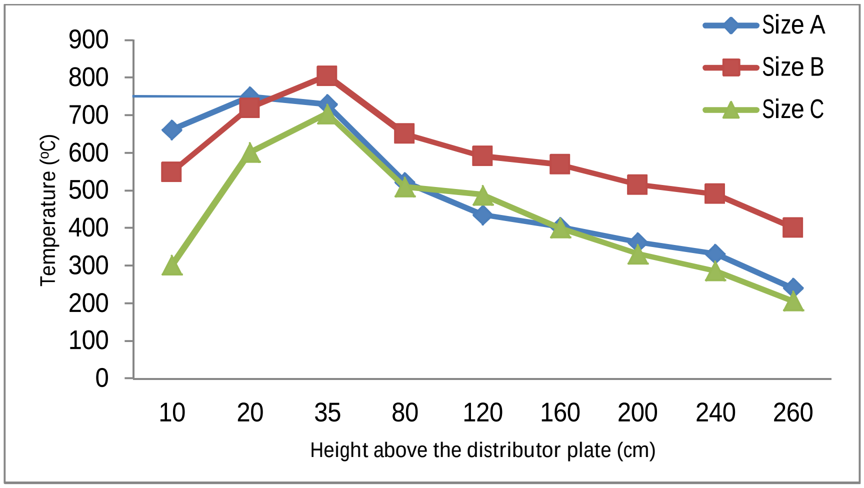


Fig. 10: A comparison of the temperature profile for the particle sizes at EA=100%

3.4 EMISSION CHARACTERIZATION

Fig. 11 shows the effect of EA on CO concentrations in the flue gas. The present results follows similar pattern and compare favorably with the work of [8, 9, 17, 18] (not shown). In all cases CO emission was rather high at low value of EA (≤30%), but plummeted to very low value at higher EA; for instance At EA=50% the values760, 856 and 570 ppm were obtained respectively for size 6-22, 2-12, and C<2 mm. This confirmed significant influence of EA on CO reductions as had been observed in other literature.

On the other hand the impact of particle size variation though noticeable was not as drastic. For instance the highest CO value of 3250 ppm was obtained at EA=30% for the biggest particle (6 – 12 mm), closely followed by 3025 ppm for size 2 – 12 mm and 2995 ppm for < 2mm. The above pattern suggested an impact though weak of the particle size variation on the CO generated. At EA≥50%, the impact of size variation was imperceptible since CO values in all cases tapered to similar magnitude. The relatively lower CO at EA=100% obtained for pulverized particles <2 mm could be attributed to the fact that at this point the combustion process had practically stopped at the inert bed, and even at the freeboard limited combustion of volatile was taking place; therefore in the midst of excess air the CO generated were largely oxidized to CO_2. The CO value obtained for all the particle sizes is below the Nigeria emission limit (calculated as 376 ppm).

NOx emission for all the particle size was lowest at EA=30%. The value of NOx from the graph confirmed influence of EA on the NOx formation in agreement with finding from other literature [8, 9, 17, 18, and 20]; Similarly SOx was noted in significant quantities in the flue gas; the trends for all the particle sizes show that it reduced as EA increased. See Fig. 13.

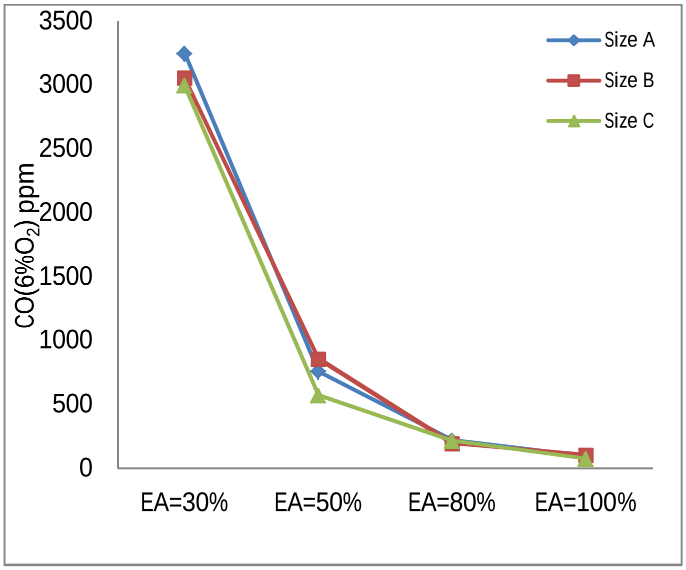


Fig. 11: Effect of EA on CO generation when firing PKS

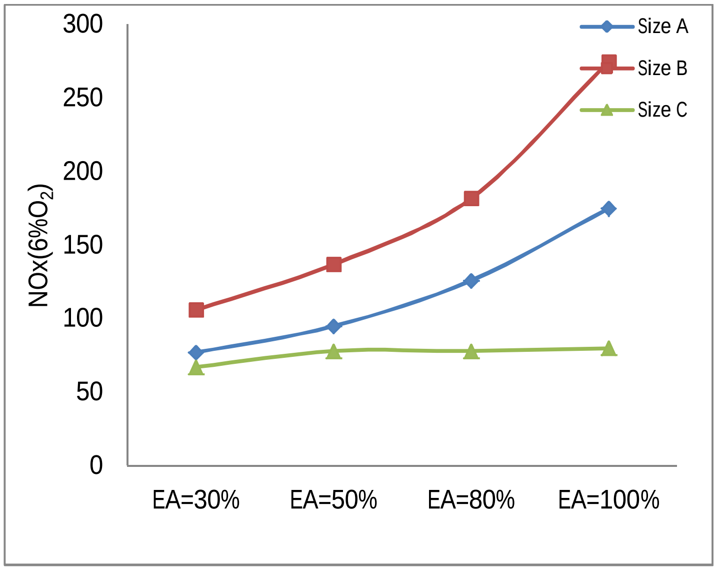


Fig. 12: A plot of NOx against the percentage excess air the fuel particle size

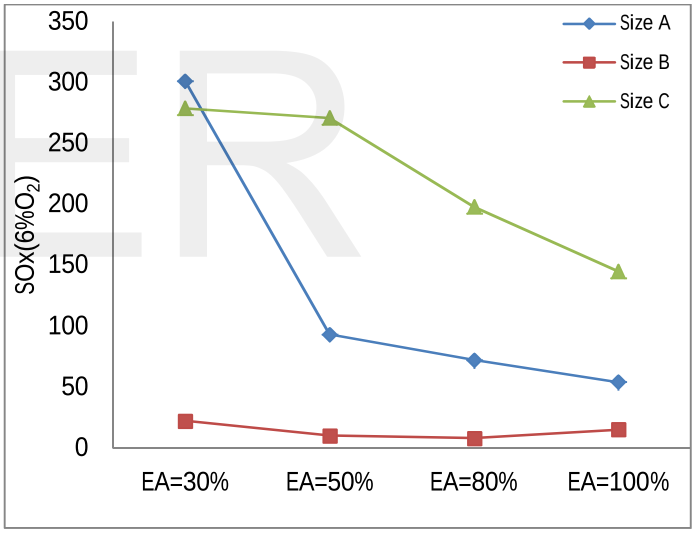


Fig. 13: A plot of SOx against the percentage excess air for each of the fuel particle size

3.5 PROGRESSION OF POLLUTANTS EMISSION WITH EA

3.5.1 CO AND SOX EMISSION

The Influence of EA and particle size variation of PKS on SOx seems similar to what was observed for CO. For the different particle sizes SOx decreased mildly with increased in EA even though the effect was almost unnoticeable on Size B. It is pertinent to note that SOx was consistently high in size C at all EA whereas for Size B it was low. The pattern of SOx yield from each of the sizes suggests strong influence of a probable reaction of the product of combustion with SOx within the inert bed. An apparent possibility is that the ashes (alkaline) from char combustion react with the SOx to substantially reduce its value as noted for size B and rapidly for size A at elevated EA. The probability that this is the case may be buttressed with unrealistically high SOx obtained for size C, which as earlier enumerated undergoes minimal combustion in the inert bed as a results of its low bulk density, which implies minimal char combustion/ash generation occurred for Size in the inert bed. Using this logic the lower value of SOx for size B compared to size A may be explained from the fact that size B being smaller its ash has larger surface area per unit area of the bubbling bed, therefore higher capacity to mop up SOx produced.

3.5.2 NOX FORMATION

As stated earlier capability to minimize NOx formation and in situ desulphurisation capacity is one of the major factor that gave FBC a competitive edge over other combustion technology, therefore understanding issues related to formation and destruction of this pollutants from combustion of fuel is significant. The fact that this experiment was conducted with complete control of the inert bed temperature with the aid of ITRU (the temperature within combustor is ensured below 800 ^{o}C) rules out meaningful thermal and prompt NOx formation.
This implies that NOx obtained were principally through oxidation of fuel Nitrogen compounds.
The effect of EA on NOx formation is quite visible from Fig. 15-18. At low EA for all the sizes NOx value was quite low. It increases almost proportionately as EA deceases. The fact however that the effect was more noticeable on Size A and B suggest significant influence of particle size as well as char oxidation on formation of NOx. It is known that Formation of NOx via fuel N could be through 2 routes [23, 24]
1. Homogeneous oxidation / gaseous compound reduction involving NCO, HCN and NH_3 (NOx precursors) [22] released as volatiles which may be represented by the following equations [22], [25]

Oxidation process
HCN+O --------- NCO+H
NCO+O --------- NO+CO
NCO+NO --------- N_2O+H
$NH_3+5/4O_2$ --------- $NO+3/2H_2O$

Reduction
NO+ $NH_3 + 1/4O_2$ ----- $N_2 + 3/2H_2O$
NO + $2/3NH_3$----- $5/6N_2 + H_2O$
NO + C(char) ---- $1/2N_2$ + CO
N_2O ----- $N_2 + 1/2O_2$
N_2O + C (char) --- N_2 + CO
N_2O + CO ----- $N_2 + CO_2$

2. Heterogeneous oxidation of nitrogen in char particles or nitrogen reduction on char surfaces,

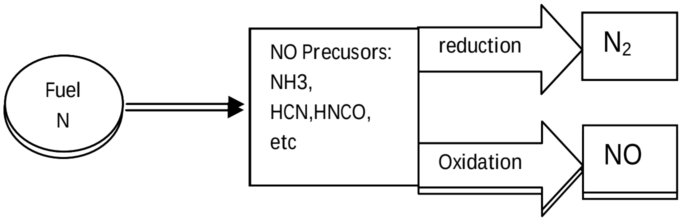


Fig. 14: A simplified sketch of conversion of fuel N [24]

It is known that for small biomass particles a significant proportion of fuel N (70-100%) is converted to NO, while for larger particles a much smaller proportion is converted [26]. This will explain the comparatively higher yield of NOx by Size B (2-6mm) compare to size A. (6-22mm). In addition since NOx for Size A and Size B appeared higher than that of Size C at all EA examined; and the freeboard combustion was predominant for size C; it might be appropriate to proposed that NOx formation during this investigation occurred mainly through heterogeneous oxidation of Char Nitrogen.

3.5.3 CORRELATION OF INFLUENCE OF EA ON CO AND NOX.

From Fig. 15-18, a relationship between CO and NOx formation and decomposition as a result of EA influence is discernable, in view of this it is possible to identify an optimum excess air that corresponds to lowest value of both. An attempt to identify this could be seen in Fig.19-21. From Fig. 19 and 20, optimum excess air for best CO and NOx is 88% and 83% for size A and B respectively. These values (150 ppm and 187 ppm for Size A and B respectively) are below the emission limits imposed by regulatory authority in Nigeria 376 ppm and 256 ppm for CO(6% O_2) and NOx(6%O_2) respectively) [27].

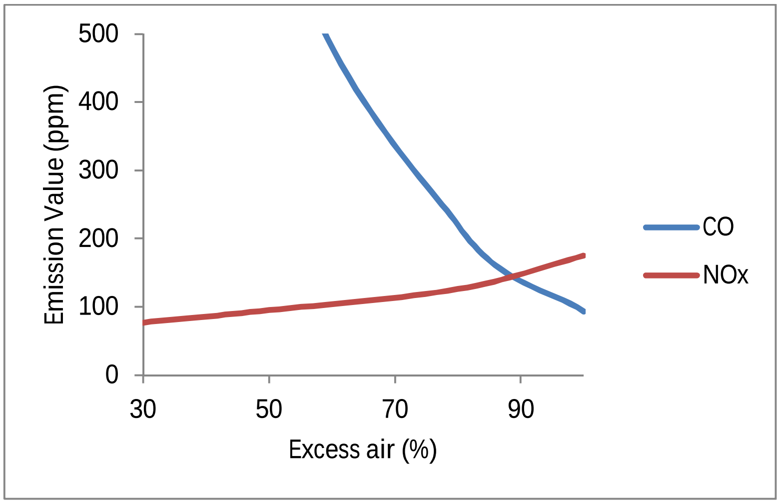
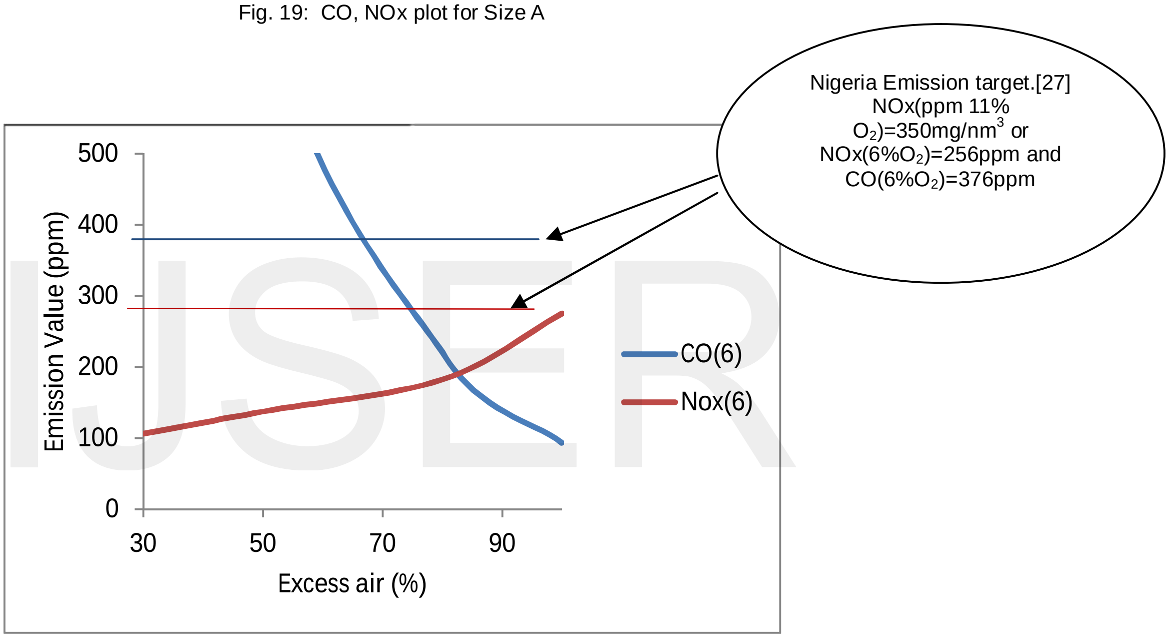


Fig. 19: CO, NOx plot for Size A



Nigeria Emission target.[27]
NOx(ppm 11%
O_2)=350mg/nm^3 or
NOx(6%O_2)=256ppm and
CO(6%O_2)=376ppm

Fig. 20: CO, NOx plot for Size B. It should be noted that the value used as emission standard was obtained from LNG website. These however differs from values posted by FEPA [28], where the limits (for Nigeria) were stated as 500 mg/m3 for NOx, 5000 mg/m3 for CO and 830 mg/m3 for SOx.

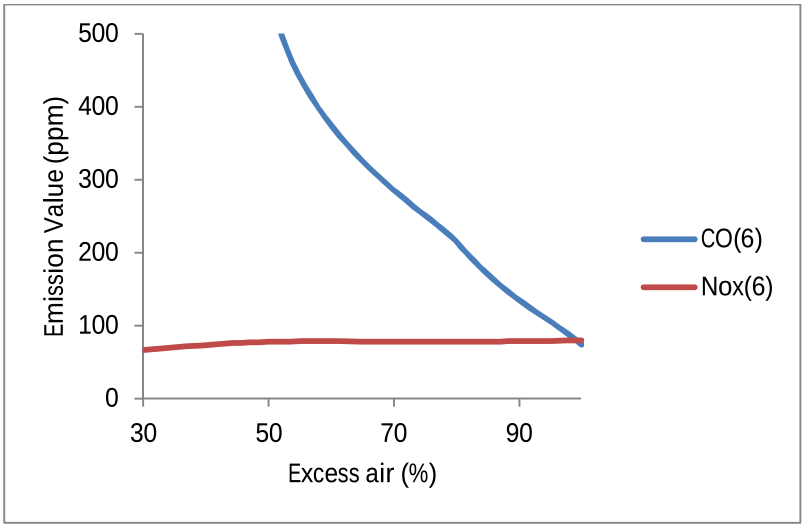


Fig. 21: CO, NOx plot for Size C

4 COMBUSTION EFFICIENCY

Combustion efficiency evaluated using equations 1-5 is shown in Table 4.

Table 4: Combustion efficiency for particle size 6 – 22 mm and 2 – 12 mm with quc assumed insignificant.

Sn	Size	O_2	CO(6% O_2)	q(ic)	CE(%)
1	6 – 22 mm	4.8	3250	1.404	98.6
2	6 – 22 mm	7.4	760	0.328	99.67
3	6 – 22 mm	9.4	220	0.095	99.9
4	6 – 22 mm	10.3	91	0.039	99.96
5	2 – 12 mm	4.7	3057	1.321	98.68
6	2 – 12 mm	6.8	856	0.37	99.63
7	2 – 12 mm	9.6	195	0.084	99.92
8	2 – 12 mm	10.1	104	0.045	99.96

Neglecting the contribution of the unburned carbon, highest combustion efficiency was obtained at EA 50-100% for all sizes. It will be observed however that temperature profile shows higher freeboard temperature at EA> 80%, an indication of higher stack losses. Furthermore, since the bulk of the unburned carbon obtained at the cyclone actually occurred at higher fluidization velocity, it will be appropriate when firing this biomass in a commercial BFBC to operate within an EA of 50%-80%.

Fig. 22: a and b [12]
a) Side view of BFBC, the upper section could be seen at the background
b) An aerial view of the BFBC during one of the experimental runs. Elutriated particles could be seen on the flange of the lower section. Inert bed temperature at this point was 801^{o}C. The dark straight line on top of the bed was the third thermocouple (temp. 627 ^{o}C). The incorporated partitioning of the combustor body into lower section and upper section makes this view possible.

5 CONCLUSIONS

Combustion of three different particle sizes of Palm kernel shell has been carried out in an experimental model bubbling fluidized bed combustor

The results indicated that efficient and environmental friendly combustion of Palm kernel shell could be achieved in a bubbling fluidized bed combustor, but fuel particle size variation have pronounced effect on thermal and emission Performance of BFBC.

It was found that Pulverized palm kernel shells (< 2 mm) could not be used in the BFBC for extended period at EA>30%. Finding clearly revealed that pulverization of PKS prior usage as fuel in BFBC is unnecessary.

On the other hand big particle sizes 2-12 mm and 6-22 mm should be fired with excess air controlled between 50 – 80% to ensure combustion efficiency greater than 99.0% and pollutant emission secured within acceptable range (complying with Nigeria emission limits).

From the experiment the following specific conclusions were made

- Palm Kernel shell from Nigeria farm may be used ‘as received’ or classified to 2-12 mm for optimum performance as a fuel for energy generation in bubbling fluidized bed combustion
- Combustion at excess air (50-80%) led to minimal CO, NOx and SOx as well as maximum combustion efficiency.
- Particle size 6-22 mm could be used for energy generation over wider degree of excess air
- Within the limit of this experimental investigation, particles sizes 6-22 mm and 2-12 mm gave acceptable results in terms of thermal characteristics and pollutants emission.

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