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Emission and Combustion Characteristics of Lafia-Obi Coal in Fluidized Bed Combustor

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Abstract. The technology of fluidized bed coal combustion (FBC) and its advantages over conventional coal burning systems is now well established and is extensively reported in the literature. There is also some emphasis in literature about the suitability of Lafia-Obi coal in FBC. However, there is little quantitative or qualitative information on theperformance of Lafia-Obi in FBC. This paper reports a study of the combustion of monosized coal fractions fed continuously to the bed via an overbed feeder. Using appropriate ASTM standards, proximate and ultimate analyses of samples of Lafia-Obi coal were carried out and the coal was then combusted in a fluidized bed. Results showed that Lafia-Obi coal has low moisture, high volatile matter and very high fixed carbon content. The volatile matter content places Lafia-Obi in the medium volatile bituminous rank. The data obtained is useful in application of fluidized bed combustion for energy production using Lafia-Obi Coal

Introduction

Nigeria is beginning to embrace coal as an alternative means for electrical power generation[1].According to Nigerian Coal Corporation [2], the middle Benue trough where Lafia-Obi is located, is considered to be a very prospective area because the depths to the mature coal zones are moderate (2-4 km). The Lafia-Obi coal Fields is geologically, the oldest coal deposit in Nigeria so far discovered and it is a potential candidate for metallurgical coke making[3,4]. Lafia-Obi Coal Field occurs in the Middle Benue trough (MBT).

The technology of fluidized bed coal combustion (FBC) and its advantages over conventional coal burning systems is now well established and is extensively reported in the literature [5,6.7). There is also sufficient emphasis in literature about the suitability of Lafia-Obi coal in FBC [3,7]. Howeverthere is also sufficient emphasis in literature about the suitability of Lafia-Obi coal in FBC [3] However, there is little quantitative or qualitative information on the performance of Lafia-Obi in FBC.

The primary basis for this work stems from the fact that the standard ultimate and proximate analyses of coals unlike other types of fuels are insufficient to provide answers to all the questions an FBC boiler designer is expected to have [5.6]. The FBC system consists of a bed of loose material lying on a porous plate with high flow resistance which enables uniform distribution of gas flowing through complex irregular channels among the particles. There isalso the issue of the complexity of the chemical composition of coal. A complex series of gaseous combustion products and a solid incombustible remnant are created by coal combustion. Hence, the complete data necessary for the calculation and design of FBC boilers can be obtained only experimentally, by measurements and observation of coal behavior in a prototype fluidized bed under real operating conditions [6]. This paper reports a study of the combustion of monosized coal fractions fed in batch to the bed via an overbed feeder. Data showing the effect of coal size, fragmentation and rate of bottom ash generation are presented.

Methodology

Samples of Lafia-Obi coal were obtained from natural deposits in Lafia, Obi Local Government of Nassarawa state. The sample were ground and sieved using a set of sieves to obtain the fuel equivalent diameter (FED). Proximate and ultimate analyses of the sample were carried out to determine the carbon, ash, volatile matter, and moisture content of the coal. The calorific value of the coal was determined using a bomb calorimeter, after which the coal was combusted in a fluidized bed.

Thermocouples and 8-channel digital readout meters were employed to measure variations in combustion and freeboard temperature. Different FED of coal were fed, at two different feed rates, into the combustor. The combustion process was quenched at different operating conditions using liquid nitrogen to determine the ash and residue characteristics. The residue recovered from the combustor which includes ash, incompletely combusted coal, fragmented coal particles and bed material was characterized. All data gathered were subjected to appropriate statistical analysis. ASTM international procedures were used as guidelines for these investigations [8-14].

The fluidized bed combustion chamber is shown schematically in Fig 1. It consists of a cylindrical steel column of 15 cm internal diameter and 100 cm in height. The combustor has a gas inlet section, cylindrical reactor body, changeable gas distributor plate, feeding section for solid fuels and an exhaust to which is fitted a gas analyzer. Table 1 provides a summary of the design parameters for the fluidized bed chamber. A sight glass, 50 mm by 30 mm is provided for visual observation of the combustion process in the reactor is provided at the top of the column. The specimen to be combusted is gravity fed to the unit via top loading.

Fragmentation index (S_f) was used to compare the effect of the size of coal particle on fragmentation. S_f is influenced by the bed temperature, the fluidizing medium, and the original size of coal particle [15]. S_f is a comprehensive index which consist of two indexes:
i) ratio of fragmentation, N_f; ii)the changing ratio of coal size due to fragmentation, F_d

$$N_f = \frac{N_{out}}{N_{in}} \quad (1)$$

N_{out}= total no.of coal particles after fragmentation; N_{out}=total no. of original coal particles in the fbc

$$F_d = \frac{\sum_{i=1}^{n} X_i d_i}{d_a} \quad (2)$$

X_i= mass fraction of particle with size I; d_i=average diameter of coal particles with size i after the fragmentation, d_a = average diameter of original coal particle put into the fluidized bed

$$S_f = \frac{N_f}{F_d} \quad (3)$$

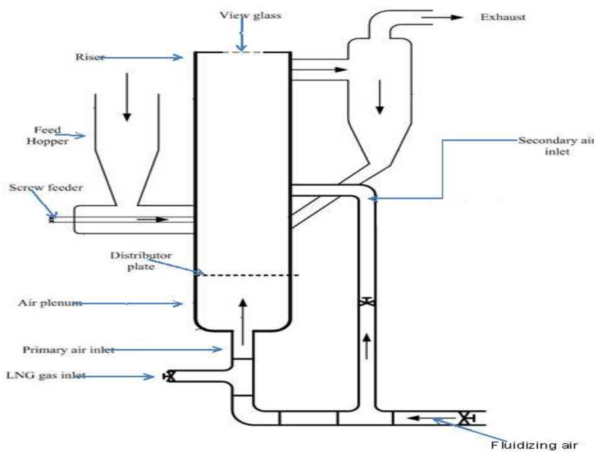
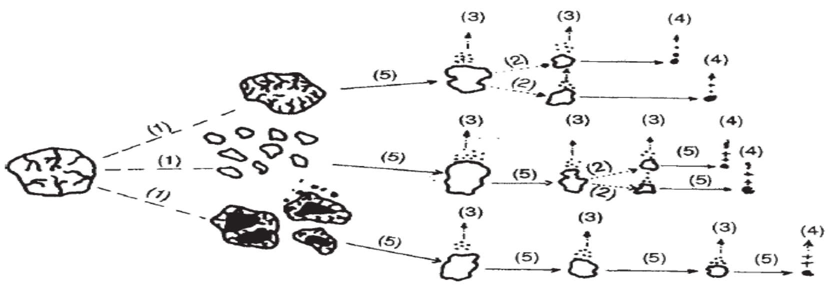


Fig 1: Schematic diagram of fluidized bed combustion system

Table 1: Experimental Conditions

Design parameters	Material/value
Type of fuel/ feed size	Lafia-Obi/(5-25mm)
Bed material / size (µm)	Sandstone/ 350-500
Bed temperature (^oC)	750-1200
Static bed height (m)	0.1
Fuel feed rate (kg/min)	0.2 & 0.3
Bed diameter (mm)	150
Fluidization Velocity(l/min)	350-2000
Pressure drop across distributor plate (mmH_2O)	43
Pressure drop across bed (mmH_2O)	428.8
Distributor plate	
No. of holes	311
Diameter of holes (mm)	1.5
Thickness (mm)	4

After inserting the coal into the combustion chamber, the coal particles change their sizes. The expected fragmentation process is shown in fig 3. It is also expected that there should be a degree of initial swelling and then contraction during devolatilization, the degree of these physical changes is a function of the type of coal and its structure. This research work does not measure the degree of swelling that may have occurred in the coal, it only provides a picture of the relationship between particle fragmentations in the fluidized bed combustor and increasing initial coal particle size.



(1) Primary fragmentation——, (2) Secondary fragmentation . . . . . ,(3) Attrition—.—.—, (4) Percolation + + +,(5) Combustion ——

Fig 3: Schematic of the order and nature of mechanical coal particle changes during residence and combustion in fluidized beds[6]

Results

Proximate Analysis. Table 2 shows the results of the Lafia-Obi coal analysis. It shows the proximate and ultimate analysis, dilation, fluidity and free swelling index obtained from the Lafia-Obi coal samples as fired. From the investigations, Lafia-Obi has a low moisture content of 2.9%. High moisture content affects the calorific value of coal and reduces the concentration of other constituents. High moisture content would also result in a decreased plant capacity and an increase in operating costs [16]. By the virtue of its moisture content, Lafia-Obi will also be suitable forcoking coal because the moisture content required by a good coking coal is 1.5%. Since a properly designed combustor chamber is designed to handle moisture contents that are much higher than 2.9 [10], one can conclude that the coal is very suitable for application in fluidized bed combustion. Lafia-Obi coal samples tested possess a volatile matter of 27.19%.

The role of volatile matter is in gasification, however in the process of combustion volatile matter is what accounts for the smoke observed during the combustion of coal because volatile matter does not form part of the coke. The ash content of value of 18.62% was observed for this coal and the ash colour was light greyish. This ash content is very high for metallurgical coke making.

Table 2: Analysis of Lafia-Obi Coal

Analysis	Value
Proximate Analysis	
Moisture (wt %)	2.91
Volatile matter (% db)	27.19
Ash (% db)	18.62
Fixed carbon (%)	51.28
	100.00
Colour of ash	Light grey
Ultimate Analysis (wt%*)	
C	59.29
H	40.61
N	2.10
S	1.81
Gross calorific (KJ kg^{-1})	23,721.40
Density (kgm^{-3})	1200
Dilation (%)	23
Fluidity (ddpm)	21
Free Swelling Index	6

* = dry-basis.

The fixed carbon content of the coal samples revealed that Lafia-Obi sample has a carbon content of 51.28%. The fixed carbon content of the coal is the carbon found in the material after volatile materials are driven off. It is used as an estimate of the amount of coke that will be yielded from a sample of coal [16].

The ultimate analysis is primarily used for the purpose of classification and ranking of the coal. The elements determined are Carbon, Hydrogen Nitrogen and Sulphur. These results are shown in table 2. The sulphur level recorded in Lafia-Obi coal is high, but the fraction by which it exceeds the standard limit is not significant. This makes it suitable for electrical power generation.

Coal Particle Fragmentation. Coal containing a large amount of volatile matter, frequently undergoes fragmentation caused by thermal shock followed by expansion of volatile and explosion of intra particles, occurring during intensive devolatilization and combustion of volatiles. Processes in the fluidized bed create favourable conditions for the Lafia-Obi coal particles fragmentation because of the fuel's moisture content and large quantity of volatile matters. One to ten char particles were produced during the devolatilization of individual coal particles. The average number of char particles produced by a single coal particle varied from two to five at the experimental conditions studied. The results are shown in Fig 4. The bigger the coal size is, the larger the value of S_f, which means that the fragmentation occur more intensely. This observation is a result of the fact that larger coal size has the larger quantity of volatile matter, which causes a higher inner pressure; therefore, the primary fragmentation occurs more intensely.

Rate of Bottom Ash Generation. The performance of Lafia-Obi coal in this fluidized bed combustor is relatively good. Three things are responsible for the quantity of bottom ash generated in the fluidized bed combustion chamber during the combustion of any material. The ash content of the coal, temperature of combustion of the coal and the rate of elutriation of the fly ash during combustion. While higher temperature of combustion leads to lower ash generation, higher rates of elutriation leads to lower quantity of residue [15,16].For all coal particle sizes combusted, being the same coal, the ash content of the coal was constant. While temperature of combustion increases with reducing coal particle sizes, the rate of fly ash elutriation increased with decreasing coal particle size. The result of the experiment is shown in Fig 5. The rate of bottom ash generated increased with increasing coal particle size. The reason for this observation as explained [15,16] is that the rate of elutriation of fly ash has a higher effect on bottom ash generation than the temperature of the combustion.

Effect of Lafia-Obi Coal Feed Size on Combustion Bed Temperature. For all combustion conditions it was noticed that after introduction of the coal particle into the combustion chamber, the ignition of the volatiles released was observed. After the volatiles ignition, the bed temperature rise was rapid and considerate (Fig 6 and 7). It was observed that the temperature rise is coal particle size dependent.

Effect of Temperature on CO emission. Theoretically, as the bed temperature increase, there is an increase in the rate of char combustion and an increase in the CO oxidation rate; this situation lowers CO concentration in the flue gases.These explain the trend observed during the course of this experimental procedure as seen in Fig 8 and 9

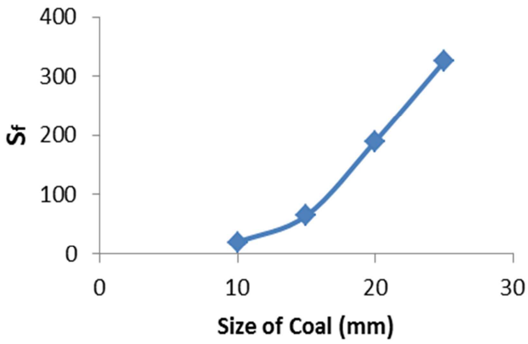


Fig 4: Profile of fragmentation index with the coal size

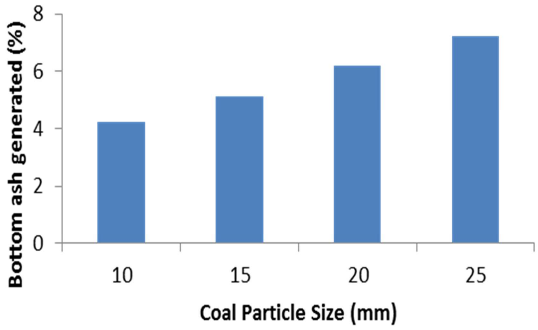


Fig5: Chart of %bottom ash generated with coal size

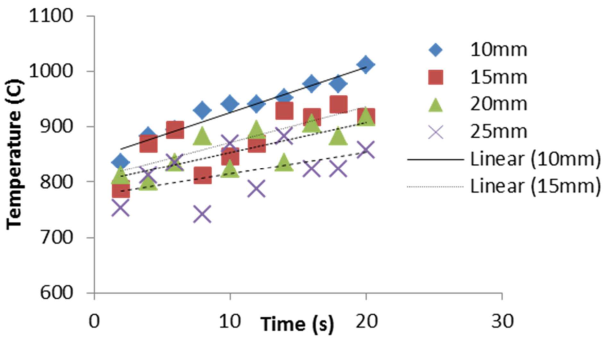


Fig 6a: Effects of coal particle size on temperature at a coal feed rate of 0.2kg/min

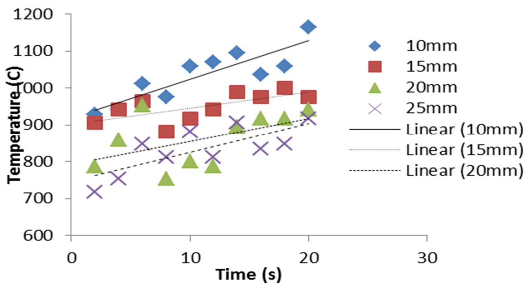


Fig 6b: Effects of coal particle size on temperature at a coal feed rate of 0.3kg/min

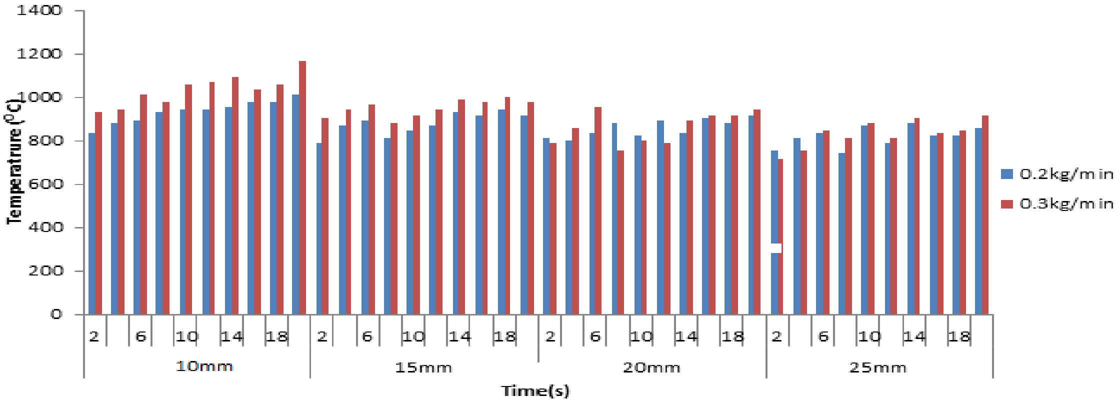


Fig 7 Summary of the effects of coal particle size and feed rate on temperature

The Figures show that there is a reduction in CO with increasing temperature. It was observed that as coal particle sizes increase, the difference in the emission level narrowed i.e. the difference between 10mm and 15mm is higher than the difference between 15mm and 20mm etc. Judging from the height of each of the lines above the x-axis, one can see that the CO concentration increases with increasing coal particle size. The level of the scatter in the graph is an indication of the level of variation exhibited by spontaneous varying rates of reaction which has been attributed to the fragmentation of the coal particles in the fluidized bed combustor. Because this experimental procedure occurred at a temperature lower than 1000°C, the NO_x measured during this experiment will be thermal NO_x. [17].

Effect of Coal Particle Size on NO_X Emission. Fig 10 and 12shows that the NO_x emission decreased with increasing coal particle size. The two Figures give a picture of the effect of coal feed rates. In support of this result [18] reported that NO_x formation increased with increasing carbon conversion,which was attributed to a decrease in NO_x reduction in the pores of char particles as they shrank. This implies that the NO_x concentration decreases with increasing particle size.

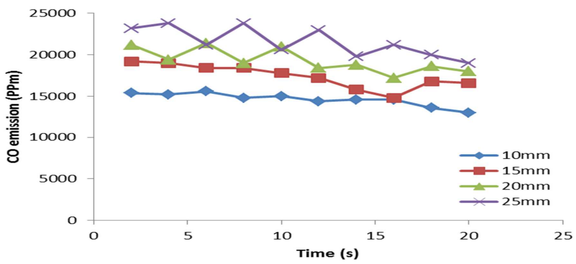


Fig 8a: Effects of coal particle size on CO emission at a coal feed rate of 0.2kg/min

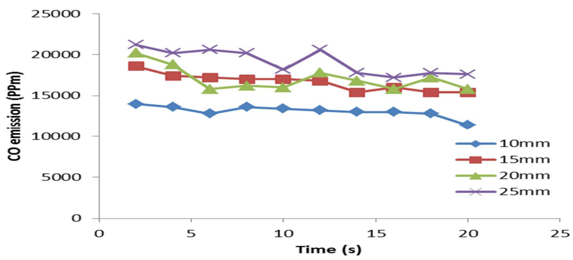


Fig 8b: Effects of coal particle size on CO emission at a coal feed rate of 0.3kg/min

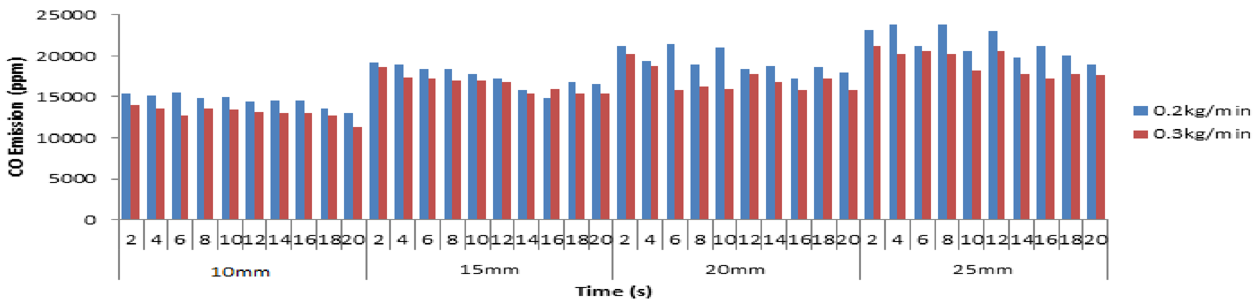


Fig9: Summary of the effects of coal particle size and feed rate on CO emission

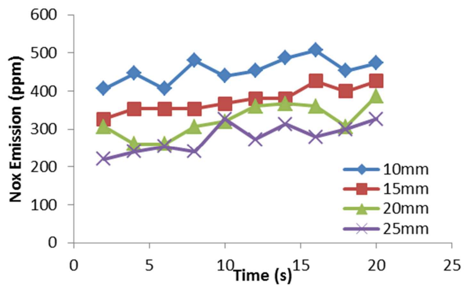


Fig 10a: Effect of coal particle size on NO_x emission at a coal feed rate of 0.2kg/min

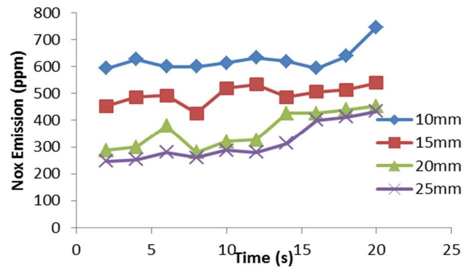


Fig10b: Effect of coal particle size on NO_x emission at a coal feed rate of 0.3kg/min

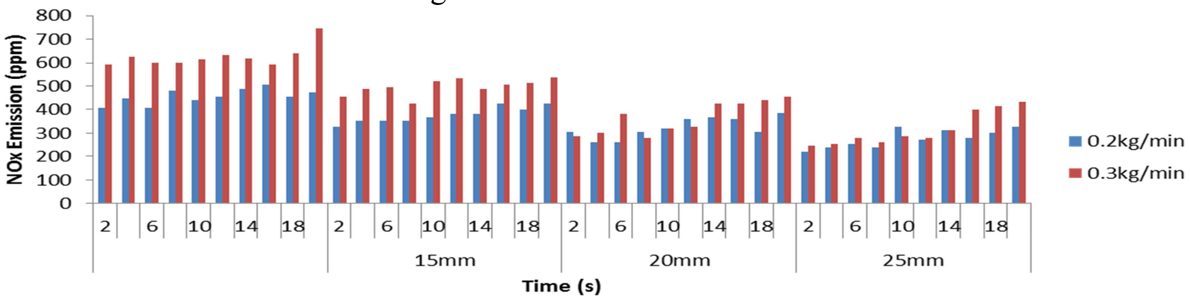


Fig 11: Summary of the effects of coal particle size and feed rate on NO_X emission

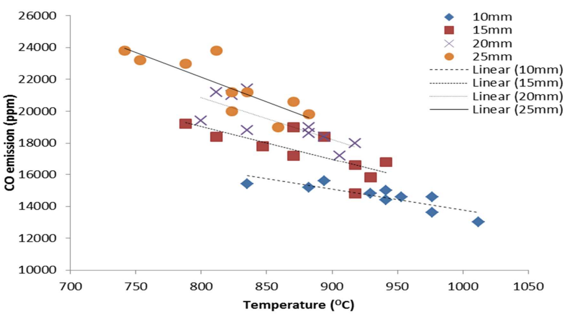


Fig 13: Effect of coal particle size & combustion bed temp on CO emission at feed rate of 0.2kg/min

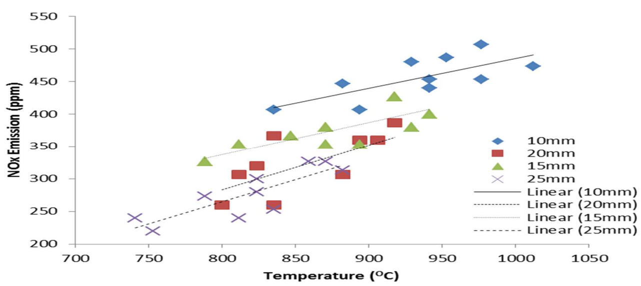


Fig 14: Effect of coal particle size and temperature on NO_X emission at a coal feed rate of 0.2kg/min

Effect of temperature on NOx emission. The NOx emissions that occur as a result of coal combustion depend primarily on how the coal is burned and only to a minor extent on properties of the coal itself. The NOx emission may be classified into (1) thermal, (2) prompt and (3) originating from fuel nitrogen. The NOx originating from coal nitrogen may be subdivided into (1) homogeneous reactions producing NOx from HCN and NH3 intermediates from coal volatile and (2) heterogeneous reactions taking place on the coal char surface from char nitrogen. Because this experimental procedure occurred at a temperature lower than 1000C, the NOx measured during this experiment will be thermal NOx [19]. The increasing NOx emission shown in Figure 4.10 to Figure 4.11 with increasing bed temperature may be due to the fact that a higher bed temperature reduces the char and CO concentrations in the combustor, decreasing the heterogeneous reduction of NO on the char surface. It was observed that the difference in the emission levels increased with decreasing particle size, i.e. the difference in the emission level between the 10mm and 15mm is higher than the difference between 15mm and 20mm.

Comparison of Lafia-Obi Emission Levels with Environmental Emission Standards. To validate the result of this investigation the United Kingdom (UK), World Bank Group (WBG) and the Chinese emission standards have been chosen for comparison. The standards chosen represent international numerical targets for maximum emissions levels for new power generation with a capacity that is less than 300 MW. These standards were chosen because they are achievable through a combination of cleaner production and they follow current regulatory trends; and promote good industrial practices. The comparison is represented in table 3. The emission levels recorded for Lafia-Obi in the table are the average values for each set of combustion condition. Several of the NO_x levels fall well below this standards however the CO levels recorded are very much outside the selected standards. Operating the combustion process under better stoichiometry is expected to reduce the measure CO emission levels. It is relevant to mention that this investigation was carried out without a secondary air supply. Secondary combustion above the bed with the use of secondary air is common when firing fuels with high volatile contents [5]. The purpose of the secondary air supply is to improve the stoichiometry of the combustion.

Table 3: Comparison of emission levels of Lafia-Obi coal with some international standards

Source		**Emission (ppm)**									
		NO_x					**CO**				
Lafia-Obi		**10mm**	**15mm**	**20mm**	**25mm**	**Mean**	**10mm**	**15mm**	**20mm**	**25mm**	**Mean**
Feed rate	0.2kg/s	455.35	376.69	323.35	277.35	358.185	14,620	17,400	19,300	21,560	18,220
	0.3kg/s	626.68	496.02	364.02	316.69	450.853	13,080	16,620	17,040	19,140	16,470
UK [a]		365.25*					870#				
China[b]		350*									
World Bank[c]		350*					950*				

* Emission Standard for New Coal Power Plants Power with Plant Size < 300 MW

\# Emission Standard for all industrial Plant combusting coal in the United Kingdom

Source

a: Notification of the United Kingdom Ministry of Industry No. 2, B.E. 2536 (1993), issued under Factory Act B.E. 2535 (1992), dated July 20, B.E. 2536 (1993), published in the Royal Government Gazette, Vol.109, Part 108, dated October 16, B.E. 2536 (1993) London.

b: Notification of the Chinese Ministry of Science, Technology and Environment published in the Government Gazette, Vol.113 Part 9 Page 220, dated January 30, 2539 (1996) and Notification of the Ministry of Science, Technology and Environment published in the Government Gazette, Vol.113 Part 9 Page 220, dated January 30, 2539 (1996)

c: World Bank Group, 1988

Conclusion

The investigation shows that Lafia-Obi coal has low moisture, high volatile matter and very high fixed carbon content. The volatile matter content, places Lafia-Obi in the medium-volatile bituminous rank. The bench-scale fluidized bed combustor methods developed in this program have been demonstrated to provide relevant information for assessing the behaviour and performance of Lafia-Obi coal in FluidizedBed Combustion. Choosing the right size of Lafia-Obi Coal, the emission of CO, NOx will be withinacceptable International standard for Electrical power generation. Analysis revealed that the temperature variation caused by variations in feed rate between 15, 20 and 25 mm during the combustion of Lafia-Obi coal in an FBC are not significant. This means that considerable financial savings can be made from combusting larger lumps of coal and not having to reduce to mined lumps into smaller feed sizes.

Proximate analysis conducted in this investigation revealed that Lafia-Obi coal has an ash content of 18% however the rate of bottom ash retention in the FBC was a minimum value of 4% to amaximum of 7%. Based on this finding, we can conclude that FBC considerable reduces the rate of bottom ash retention during the combustion of Lafia-Obi coal. The data obtained is useful in application of fluidized bed combustion for energy production using Lafia-Obi Coal

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