Experimental Study on Nigeria Biomass Combustion in a Fluidized Bed Combustor

J.O. NORDIANA[1], O. IGHODALO[2], O. OBODEH[3]
[1, 2, 3] *Department of Mechanical Engineering, Ambrose Alli University, Ekpoma, Nigeria*

Abstract -- This work investigates the combustion of five kinds of Nigerian biomass in an atmospheric bubbling fluidized bed combustor. The combustion chamber is a steel cylinder with 145mm internal diameter and 2400mm height. Tests were conducted on coconut shell, rice husk, corn cobs, groundnut husk and sawdust-wood. Excess air was varied for each fuel. Temperature variation along the combustor height and the flue gas emissions from the combustor exhaust were measured and thereafter the combustion efficiency for each biomass fuel was determined. Results gave maximum combustion efficiencies of 96.6%, 96.7%, 96.2%, 97.9% and 98.2% for coconut shell, rice husk, corn cobs, groundnut husk and sawdust-wood respectively at 80% excess air except for coconut shell where it occurred at 65% excess air. The major gaseous (CO and NO) emissions were at levels which were less than the U.K. environmental emission limits permitted for new fluidized bed combustor of biomass fuels.

Indexed Terms: biomass, combustion efficiency, fluidized bed combustion, emissions, excess air

I. INTRODUCTION

Biomass fuels provide an attractive primary energy source because of their renewable nature, neutrality with respect to green house-compound generation and limited formation of pollutants. In Nigeria, enormous amount of biomass wastes mostly in the form of agricultural wastes estimated to be about 168.49 million tonnes are generated annually [1]. These biomass wastes are generally disposed of by direct open burning in fields or left to waste in the farm without energy recovery. The utilization of biomass wastes in energy production is a promising option since biomass is renewable and CO_2 neutral fuel. In addition, utilization of biomass fuel as an energy source reduces the rate of fossil fuel depletion and alleviates the growing waste disposal problem. Moreover, managing biomass energy which can be stored and produced on demand is easier than managing other intermittent renewable energies [2].

Fluidized bed combustion (FBC) is widely used for burning different biomass fuels [3, 4]. 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 [5].

Several experimental investigations have been carried out to date on fluidized bed combustion of different biomass wastes. Permchart and Kouprianov [6] carried out experimental studies in a conical fluidized bed combustor with different biomass fuels: sawdust, rice husk and baggasse. The results showed that for the maximum combustor load and excess air of 50 to 100%, a combustion efficiency of over 99% could be achieved when firing sawdust and baggasse. Srinivasa-Rao and Venkat-Reddy [7] investigated the effect of secondary air addition on combustion efficiency of sawdust in a bubbling fluidized bed combustor with an enlarged disengagement section. The temperature profiles for sawdust with an increase in fluidization velocity along the vertical height above the distributor plate showed that substantial burning of fuel particles took place in the freeboard rather than complete burning within the bed. Maximum combustion efficiency of 99.2% was attained at 65% excess air. Madhiyanon et al [8] investigated the effect of fluidization velocity, excess air and combustor loading in a short combustion chamber fluidized bed combustor burning rice-husk and found that the system could operate without any secondary solid as bed material and could achieve high combustion efficiency of 99.8%. Suranani and Goli [9] investigated the major gaseous emissions from a fluidized bed with a rectangular shaped bed firing sawdust. Experiments were conducted to study the effect of fuel feed rates for various values of excess air and for various particle sizes. When all other parameters were kept constant, the optimum excess air was established to be 50% for obtaining maximum combustion efficiency of 99.2% with an acceptable carbon monoxide emission.

However, it was found that there were insufficient investigations for Nigerian biomass, which varies widely in caloric value and analysis in fluidized bed combustor. In this paper, an attempt was made to study the combustion characteristics of five different kinds of Nigerian biomass. The biomass wastes employed are coconut shell (CS), rice husk (RH), corn cobs (CC), groundnut husk (GH) and sawdust-wood (SW). The objective of the present work was to study the effect of excess air on the temperature variation in the fluidized bed combustor and the major gaseous (CO and NO_x) emissions from the combustor as well as determine the combustion efficiency of each of the biomass fuels employed.

II. EXPERIMENTAL SETUP

The apparatus used for the present work was an atmospheric bubbling fluidized bed combustor. The schematic diagram

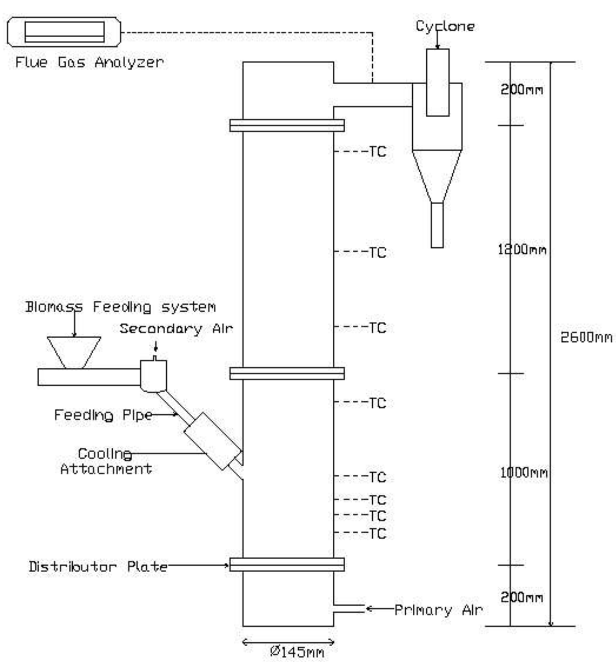

Fig. 1: Schematic diagram of the fluidized bed combustor

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 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.

The combustor is equipped with a continuous over-bed fuel feeding system which consists of a hopper and a screw conveyor. The screw conveyor shaft was driven by a 1hp variable speed electric motor which was used to control the biomass fuel feed rates. Biomass fuels were fed through the hopper. After passing through the conveyor, the fuels moves by gravity through a feeding pipe inclined at an angle of 45^0. Secondary air was introduced through this pipe and enters the combustor at a height of 500mm above distributor plate. The primary air and secondary air were supplied by a 3hp centrifugal blower. A water-cooled jacket was fitted around the feeding pipe to prevent the fuels from burning inside the feeding pipe before entering the combustor.

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 (800^0C) by adjusting the flow rate of the cooling water. This was to prevent bed agglomeration and formation of oxides of Nitrogen through the thermal-NO_x 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 (600^0C), normally above the ignition temperature of the biomass fuels. During combustion of the biomass fuels, 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 variation inside the combustor, Ni/Cr – Ni thermocouples (TC), type K with a resolution of 1^0C 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. The thermocouple probes were each connected to digital display units. The CO and NO_x 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 measured 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. [10] and Saxena and Jotshi [11] based on the knowledge of the compositions of the fuel and flue gases as well as the fractional excess air supplied using the following relation:

$$\eta_{CE} = \frac{(Q_F - Q_L)}{Q_F} x\, 100\% \qquad (1)$$

where η_{CE} is the combustion efficiency, 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.

a) Experimental Procedure:

The selected biomass fuels were gradually fed in-turn into the combustor through the hopper. The fuel feed rate were adjusted to 8.14kg/hr, 7.03kg/hr, 6.10kg/hr, 6.75kg/hr and 6.38kg/hr for CS, RH, CC, GH and SW respectively. The ratio of primary to secondary air was fixed at 70:30. The primary and secondary air velocities were adjusted to 35% excess air for each biomass fuel. In addition, the water flow rate was adjusted such that the bed temperature remains steady at 800^0C. The conditions within the combustor were allowed to stabilize for about 5 minutes and thereafter readings were taken. These procedures were repeated for 50%, 65%, 80% and 100% excess air respectively.

b) Biomass Fuels Characteristics and Inert Bed Material:

The biomass wastes were collected from local mills and crushed. The mean particle size of inert bed material (sand) and each biomass fuel were determined by a sieve shaker with different sieve sizes. The bulk density, true density and static voidage of biomass fuels and sand were also determined and the results are shown in Table 1. The proximate and ultimate analysis of the selected Nigerian biomass fuels are shown in Table 2

Biomass Fuels and sand	CS	RH	CC	GH	SW	sand
Mean particle size (mm)	3.2	1.59	2.66	2.76	1.77	2.965
Bulk density (kg/m^2)	519.48	192.31	166.97	184.74	174.65	1454.55
True density (kg/m^2)	1142.86	967.74	534.78	626.32	648.72	2461.54
Voidage	0.55	0.80	0.69	0.71	0.73	0.409

Table 1: Mean particle size, bulk density, true density and voidage of Biomass Fuels

Selected Biomass Fuel		CS	RH	CC	GH	Sawdust
Proximate analysis (% by mass, as received)	Fixed Carbon	21.38	16.21	13.34	20.80	16.00
	Volatile Matter	70.35	69.87	76.43	69.62	74.30
	Moiture	4.89	2.30	4.60	6.69	6.40
	Ash	3.38	13.92	5.63	2.89	3.30
Ultimate analysis (% by mass, as received)	Carbon	46.24	42.03	46.19	47.64	49.68
	Hydrogen	7.31	5.23	5.43	7.36	5.42
	Oxygen	42.75	38.63	41.59	41.38	39.31
	Nitrogen	0.22	0.13	0.92	0.51	0.20
	Sulphur	0.10	0.06	0.24	0.22	0.09
	Ash	3.38	13.92	5.63	2.89	5.30
Higher Heating Value (MJ/kg, dry basis)		17.41	15.21	18.36	16.82	17.42

Table 2: Proximate and Ultimate Analysis of Selected Biomass Fuel

III. RESULTS AND DISCUSSION

a) Temperature Variation:

Plots of temperature variation along the combustor axial height for the biomass fuels at various percentage excess air values were obtained as shown in fig 2 to fig 6. As each biomass fuel was 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 by-pass the bed and burn in the freeboard while a high percentage of the high carbon content char left after the devolatilization, was burnt in the bed. The bed temperature was fairly constant for the various excess air values as shown in fig 2 to fig 6.

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 [3]. 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 to fig 6.

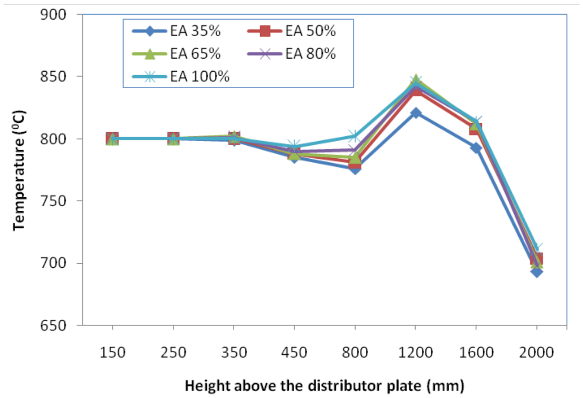

Fig. 2: Temperature variation along combustor axial height for CS combustion

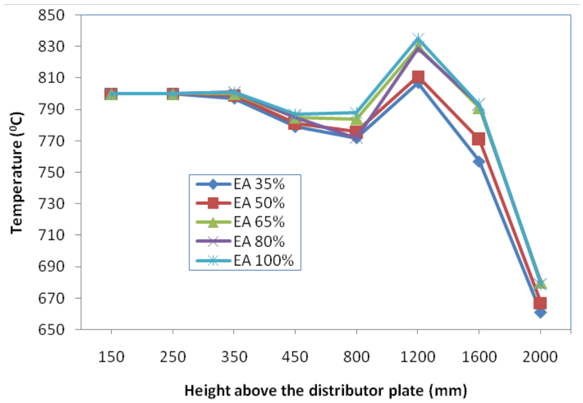

Fig. 3: Temperature variation along combustor axial height for RH combustion

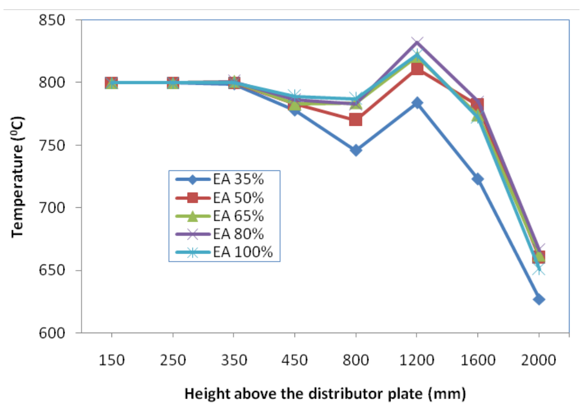

Fig. 4: Temperature variation along combustor axial height for CC combustion

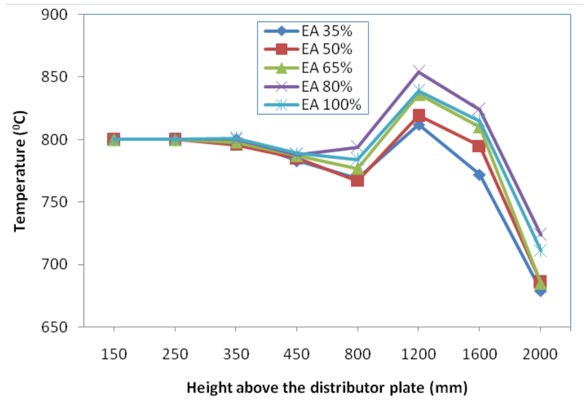

Fig. 5: Temperature variation along combustor axial height for GH combustion

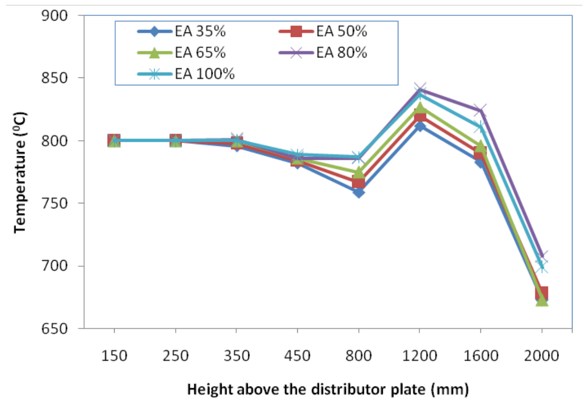

Fig. 6: Temperature variation along combustor axial height for SW combustion

b) Flue Gas Emissions:

In other to enable comparison of the emissions, the measured emissions from the combustor exhaust were converted to emissions at 6% O_2 in the flue gases as recommended by TSI [12].

The CO and NO emissions at 6% O_2 in the flue gases for the various biomass fuels combustion were plotted respectively against the percentage excess as shown in fig 7 and fig 8.

CO emissions decreases as percentage excess air increases as indicated in fig 7. 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. [13] and Ninduangdee and Kuprianov [4]. At the optimum excess air, the CO emissions at 6% O_2 in the flue gases were 88ppm, 8ppm, 5ppm, 6ppm and 6ppm for CS, RH, CC, GH and SW respectively.

As shown in fig 8, 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. [13] and Ninduangdee and Kuprianov [4]. The maximum values of NO emissions at 6% O_2 in the flue gases were 82.78ppm, 49.60ppm, 99.73ppm, 102.62ppm and 77.91ppm for CS, RH, CC, GH and SW 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 [14] which is 120.1ppm

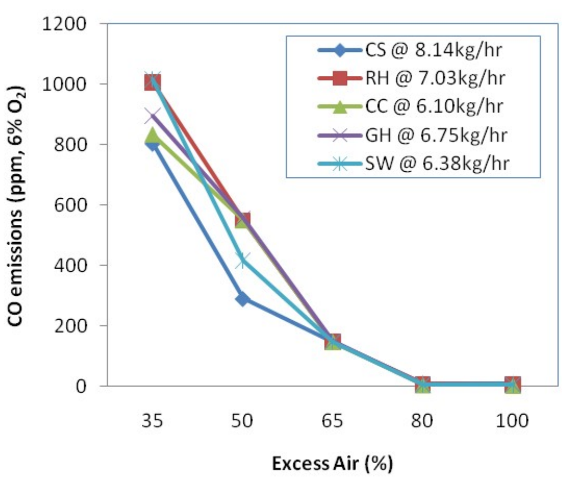

Fig. 7: CO emissions at 6% O_2 in flue gases for the various biomass fuels combustion

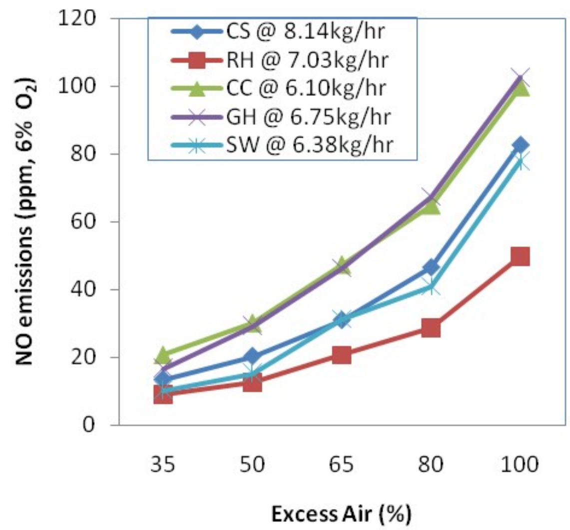

Fig. 8: NO emissions at 6% O_2 in flue gases for the various biomass fuels combustion

(150mg/m^3) for CO and 186.8ppm (250mg/m^3) for NO at 6% O_2 in flue gases.

c) Combustion Efficiency:

Combustion efficiency is a very good measure of the performance of fluidized bed combustor [4]. The combustion efficiency was plotted against the percentage excess air for each of the biomass fuels combustion as shown in fig 9. The highest combustion efficiencies of 96.6%, 96.7%, 96.2%, 97.9% and 98.2% for CS, RH, CC, GH and SW respectively, occurs at 80% excess air except for CS where it occurs at 65% excess air. This means the combustion efficiency increases with increase in excess air up to a maximum value 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 [15]. However, any further increase in the percentage excess air above the optimum value (80% for all the biomass fuels except for CS where it was 65%), 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 [4]. 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.

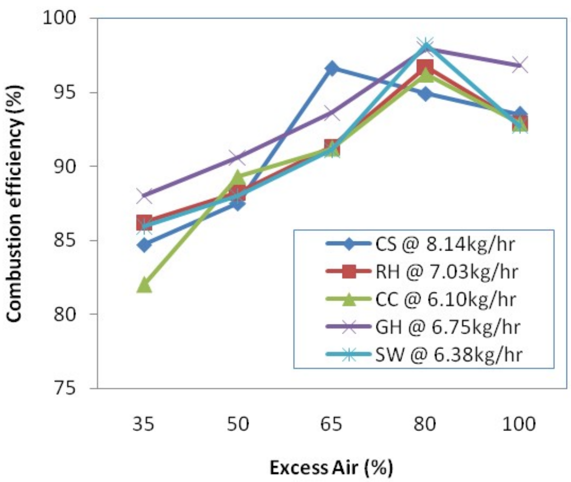

Fig. 9: Combustion efficiency for the various biomass fuels combustion at various percentage excess air

IV. CONCLUSION

The fluidized bed combustor was successfully tested for burning coconut shell, rice husk, corn cobs, groundnut husk and sawdust-wood at fuel feed rate of 8.14kg/hr, 7.03kg/hr, 6.10kg/hr, 6.75kg/hr and 6.38kg/hr respectively while varying excess air from 35% to 100%. There was a general trend of temperature variations along the combustor axial height for all tested biomass fuels. The maximum combustion efficiency for all the biomass fuels combustion occurred at 80% excess air except for coconut shell where it occurred at 65% 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 emissions for the biomass fuels combustion were less than the U.K environmental emission limit permitted for new fluidized bed combustor of biomass fuels which are 120.1ppm for CO and 186.8ppm for NO at 6% O_2 in the flue gases.

Fluidized bed combustors can be employed for the purpose of utilizing the abundant biomass resources available in Nigeria for energy production and hence reduce the over-dependence on crude oil as a major source of energy in Nigeria.

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support from Ambrose Alli University, Ekpoma, Nigeria.

REFERENCES

[1] K.J. Simonyan, O. Fasina. –Biomass resources and bioenergy potentials in Nigeria. African Journal of Agricultural Research. 2013, 8: 4975 – 4989.

[2] N.D. Tung, D. Steinbrecht, T. Vincent, –Experimental investigations of extracted rapeseed combustion emissions in a small scale stationary fluidized bed combustor. Energies. 2009, 2: 57 – 70.

[3] F.M. Okasha, S.H. El-Emam, H.K. Mostafa, –The fluidized bed combustion of a heavy liquid fuel. Experimental Thermal and Fluid Science. 2003, 27: 473 – 480.

[4] P. Ninduangdee, V.I. Kuprianov, –Combustion of oil palm shells in a cone-shaped Fluidized bed combustor using dolomite as the bed material to prevent agglomeration. Energy procedia. 2014, 52: 399 – 409.

[5] V.I. Kouprianov, W. Permchart, –Emission from a conical fluidized bed combustor fired a biomass fuel. Applied Energy, 2003, 74: 383 – 392.

[6] W. Permchart, V.I. Kouprianov, –Emission performance and combustion efficiency of a conical fluidized bed combustor firing various biomass fuels. Bioresource Technology, 2004, 92: 83 – 91.

[7] K.V.N. Srinivasa-Rao, G. Venkat-Reddy, –Effect of secondary air injection on the combustion efficiency of sawdust in a fluidized bed combustor. Brazilian Journal of Chemical Engineering, 2008, 25: 129 – 141.

[8] T. Madhiyanon, P. Sathitruangsak, S. Soponronnarit, –Combustion characteristics of rice-husk in a short-combustion-chamber fluidized bed combustor. Applied Thermal Engineering 2010, 30: 347 – 353.

[9] S. Suranani, V.R. Goli, –Modeling fluidized bed combustion of rice husk. 2012

International Conference on Chemical, Civil and Environment Engineering, Dubai, U.A.E., 2012, pp. 305 – 308.

[10] S.C. Saxena, N.S. Rao, R.R. Koganti, –Coal combustion studies in a fluidized bed test facility. Energy, 1991, 17: 579 – 591.

[11] S.C. Saxena, C.K. Jotshi, –Fluidized bed incineration of waste materials. Progress in Energy and Combustion Science, 1994, 20: 281 – 324

[12] TSI Incorporated. –Combustion analysis basics: An Overview of measurements, methods and calculation used in combustion analysis. TSI incorporated, U.S.A.,2004, p.35

[13] T.O. Raji, O.M. Oyewola, T.A.O. Salau, –Combustion of 'as received' palm kernel shell in a bubbling fluidized bed combustor. 2012 Proceedings of the 9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Malta.

[available online]: http://hdl.handle.net/2263/42960 Date assessed: 21/9/2016

[14] Environment Agency, –Integrated pollution prevention and control (IPPC) sector guidance note: combustion activities. Environment agency, Bristol, 2002, p.128

[available online]: www.environment-agency.gov.uk Date assessed: 13/02/2017

[15] S. Patumsawad, –Fluidized bed combustion of oil palm solid waste. The Journal of KMITNB, 2002, 12: 15 – 20.