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Development of an Experimental Model Bubbling Fluidized Bed Combustor for Combustion of Biomass

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ABSTRACT

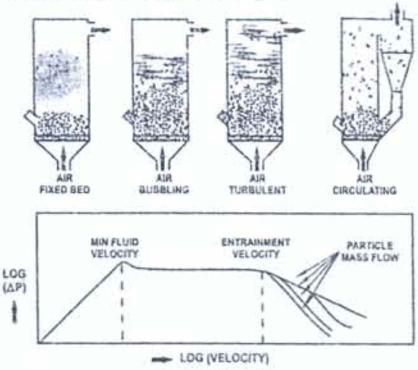
Fuel flexibility and capacity to burn broad spectrum of fuels at high combustion efficiency with minimum emissions of greenhouse gases are few of several key advantages fluidized bed combustion technology has over other existing combustion technology. This report examines the design, development and testing of an experimental model Bubbling fluidized bed combustor (BFBC). The developed BFBC has unique inert bed's temperature regulating system which implies that the use of external source of cooling the inert bed such as embedded water cooled coil might be unnecessary. Fluidizing air pre-heater / Biomass feeding pipe's cooling attachment which attempt to prevent biomass from burning before entering the fluidized bed is another important feature of this BFBC. The Combustor body was fabricated from 150mm diameter, 2900mm tall type 304 stainless steel pipes, divided into 5 modules. Coconut shell and Palm kernel shells were burnt successfully in the combustor.

As a result of its numerous advantages over conventional combustion technology, Fluidized Bed Combustion (FBC) has been identified as a most viable means of generating renewable energy, therefore success with small BFBC like the one described here could be applied to building commercial size BFBC for power generation in Nigeria and Africa sub-region.

Keywords: Bubbling Fluidized Bed, Combustion, Biomass, Renewable energy, Experimental model

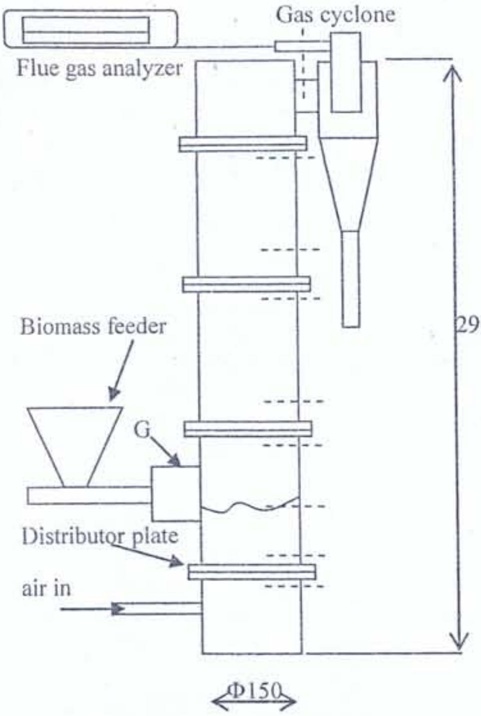
INTRODUCTION

Bubbling fluidized bed combustor (BFBC) have different components functioning in unison to burn wide variety of fuels in an efficient and environmentally friendly manner. It employed strong stream of fluidizing air with approach velocity V_o such that V_o is greater than the minimum fluidizing velocity U_{mf} and less than the full fluidization velocity U_{ff} ; $U_{mf} \leq V_O \leq U_{ff}$; at this stage the fluidization regime is characterized by bubbles formation and vigorous mass turbulence, the bed particles exhibits property of fluid and assumes appearance of a boiling liquid – the bed at this point is said to be in Bubbling Fluidized Stage. This fluidization characteristics and the selected feed rate are essentially the basic criteria that determine the dimension of any BFBC and capacity of its auxiliary equipment e.g. Blower, the Biomass feeder, cyclone separator etc. When $V_o < U_{mf}$ (minimum fluidizing velocity) the bed material remain a fixed bed (packed bed), at the other extreme when $V_o \geq U_t$ (terminal velocity) the bed mobilizes and transition to Circulating Fluidized Bed (CFBC) occurred see fig 1.



Fixed, Bubbling & Fast Fluidized Beds: As the velocity of a gas flowing through a bed of particles increases, a value is reached when the bed fluidizes and bubbles form as in a boiling liquid. At higher velocities the bubbles disappear; and the solids are rapidly blown out of the bed and must be recycled to maintain a stable system.

Fig.1 A schematic drawing shows transition from packed bed to circulating bed [15].



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

Fig 2: Schematic drawing of the BFBC

The potential of FBC to fire various fuels, including difficult to burn fuels and biomass at high efficiency and in an environmentally friendly manner has been investigated by several authors. [1] shows that sawdust could be combusted in BFBC at over 99% efficiency and [4] achieved over 90% combustion efficiency when firing Palm Kernel Shell (PKS) in a BFBC. Literature such as these abounds, however high thermal efficiency as obtained above is not easily achievable in conventional combustor, for example [16] achieved less than 32% thermal efficiency in several experiments using inclined grate burner to combust PKS. In view of this, importance of fluidized bed combustion technology could not be overstressed, furthermore it is worthy of note that Nigeria [14] and most part of Africa sub-region lack experience with firing of biomass to generate energy in BFBC. This report examines the development of a standard BFBC for combustion of Biomass.

BASIS FOR DESIGN OF THE BFBC

The following were used as the basis for estimating the size of BFBC.

A) Experimental model implies immense size is not critical, hence to ensure minimal spending smaller size BFBC and low feed rate were considered. Feed rate f_d is selected as 4kg/hr – 6kg/hr for economy reason.

B) Diameter Φ was chosen as 150mm, because the selected feed rate requires appropriately small cross sectional diameter, furthermore this f_d and Φ lies within a range that is popular and known to have been used successfully in literature ([2],[3],[4]).

C)Height (H): fuels are made up of fixed carbon, moisture, ash and Volatile matter, because of the ways volatile burnt, height of BFBC needs to be significant. Volatile are normally released at the bed and a major proportion of it burns in the freeboard, it therefore follows that to efficiently burn fuel such as Biomass (high volatile matter content) a greater height will be needed for higher value of feed rate (f_d). [4] used BFBC with 150mm diameter, height=2.3m and f_d, < 2.2kg/hr, therefore the developed BFBC which is designed for a higher feed rate should logically have height equal or greater than [4]. H was chosen as 2900mm in the current work.

D)A necessary requirements for BFBC is that the bed must be secured in bubbling fluidized mode therefore at the selected feed rate the velocity Vo of the fluidizing/combustion air must satisfy the condition; $U_{mf} \leq V_O \leq U_{ff}$

E)Typical temperature within BFBC is 800°C to 950°C: BFBC must operate at sufficiently low temperature to inhibit formation of NO_X and to prevent Ash fusion in the inert bed. In the developed BFBC an electronic control unit was incorporated to regulate/limit the inert bed temperature to desirable value. The electronic control unit comprises of a Temperature controller, a type K thermocouple, and two 40Amps contactors, the circuit is constructed in such a way that when the pre-set temperature is achieved the biomass feeder motor is de-activated. See fig 6b. This is a neater, more precise and less cumbersome method than the water-cooled metal tube that is often used.

NOMENCLATURE

BFBC	Bubbling Fluidized Bed Combustor	
FBC	Fluidized Bed Combustion.	
PKS	Palm Kernel Shell	
CS	Coconut Shell	
V_o	fluidizing air approach velocity	(m/s)
U_{ff}	Full fluidization velocity	(m/s)
U_{mf}	minimum fluidization velocity	(m/s)
H	Total height of the Combustor	(m)
f_d	Biomass feed rate	(kg/hr)

C_d	coefficient of discharge through orifice	
A_p	Cross sectional area of the particle	(m)
r	radius of the particle	(m)
V_S	Volume of the solid particle	(m^3)
g	acceleration due to gravity	(m/s^2)
d_p	Inert particle diameter	(m)
D	Diameter of the screw	(m)
P	pitch	(m)
N	Speed of the Conveyor screw	(rpm)
k	conveyor screw inclination	
T_b	inert bed temperature	(K)
A_r	Archimedes Number	
ΔP	Pressure drop	(N/m^2)
Re_{mf}	Reynold Number at minimum fluidization velocity	
d_o	diameter of orifice	(m)
N_{or}	Numbers of orifices on the bubblecaps	

Greek Letters

Φ	BFBC internal diameter	(m)
μ_g	Viscosity of the fluidizing air	(kg/ms)
ρ_p	Density of the particle	(kg/m^3)
ρ_f	density of the fluidizing air	(kgm^3)
β	feed coefficient (always less than 1)	
ʎ	ytisned kluB	(kg/m^3)
η	Cyclone collection efficiency	

DESIGN ANALYSIS

With $f_{d,}$, Φ and H established, the dimension of auxiliary components listed below were evaluated.

1. Centrifugal blower
2. Distributor plates
3. Standpipes/bubble caps specifications and Numbers
4. Biomass Feeding Unit
5. Cyclone Separator.

CENTRIFUGAL BLOWER

Palm kernel shell (PKS) and Coconut shell(CS) are used as sample fuels for the present design. Typical proximate and ultimate analysis of PKS and CS from literature ([4], [5]) are shown below

Table1: Proximate analysis (% by mass on dry basis,)

Items	PKS[4[	CS[5]
Fixed carbon	18.56	6.69
Volatile matter	72.47	90.31
Ash	1.01	3.00

Table2: Ultimate Analysis (% by mass on dry basis)

Elements	PKS	CS
Carbon	45.61	46.22
Hydrogen	6.23	5.2
Oxygen	37.51	41.63
Nitrogen	1.73	0.26
Sulphur	NIL	NIL
Ash	1.01	3.00
NCV KJ/kg	18000	17408

Minimum and maximum air requirement for combustion (using PKS)

Relevant combustion equations may be written as;

$2H_2 + O_2 = 2H_2O$

$C + O_2 = CO_2$

$N_2 + O_2 = 2NO$

Using the above, Oxygen requirement is calculated as in table 3

Table 3: Oxygen requirement for combustion of 1kg of PKS

Elements	kg/kg of fuel	O_2 needed
Carbon	0.4561	1.216
Hydrogen	0.0623	0.4984
Oxygen	0.3751	0
Nitrogen	0.0173	0.0198
Sulphur	0	0
Ash	0.0101	0

A key objective of fluidized bed combustion of fuel is to inhibit formation of NOx a major GHG, this is achieved via limiting the combustion temperature to a level below threshold of thermal NOx formation (around 1400°C). In FBC temperature is generally below 950°C hence oxygen required for combustion of atmospheric nitrogen may be justifiably excluded.

Therefore oxygen requirement (kg) = 1.7342 oxygen needed from the fluidizing air = 1.7342-0.3751=1.3591kg,

Since oxygen account for approximately 23.3% of air, then air requirement for complete combustion of 1kg of PKS is 5.833kg.

Using f_d, minimum and maximum air requirement is calculated as below;

Blower Air_{min} = 23.32kg/hr
Blower Air_{max} =34.988kg/hr.

These are the minimum and maximum theoretical air requirement, while the minimum figure is in order, the figure obtained for maximum must be increased since it is a known fact that stoichiometric air is never sufficient for complete combustion, furthermore to enable comprehensive emission and combustion analysis of any given fuel it is appropriate to investigate the effect of up to 100% excess air (100% EA); this implies that our target maximum air requirement should actually be close to 80kg/hr (2x35kg/hr).
A single output Centrifugal Blower (powered by 2850rpm, 3hp, 3phase electric motor and rated maximum output 0.6944m³/s at 40°C)equipped with 2inch Gate valve for regulating the air flow-rate from 0 to maximum was employed.

DISTRIBUTOR PLATE

The Distributor plate, act as a support and passage via which fluidizing / combustion air enters the inert particles to ensure their constant agitation and to prevent formation of zone of de-fluidization. The distributor plate is made from stainless steel with numbers of bubble-caps arranged in a definite geometric pattern. Each bubble-cap bears numbers (N_{or}) of orifice of appropriate diameter (d_o) via which the fluidizing air enters the inert bed.
Distributor plate with bubble caps though more complicated to fabricate has several advantages over other designs, such as

i. It prevent sand from leaking through the fluidizing orifices.

ii. The undisturbed layers of sand below the orifices act as heat shield, hence insulation for the distributor plate..

N_{or} AND d_o ARE ESTIMATED AS FOLLOWS

The total pressure drop in a fluidized bed is summation of three components

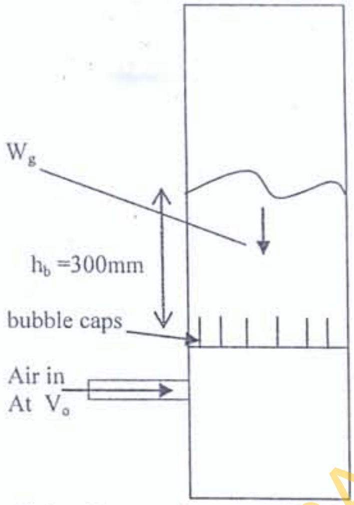


Fig3: schematic drawing of the distributor plate showing the effective height of the bed as h_b

$\Delta P = \Delta P_S + \Delta P_w + \Delta P_f$

ΔP_S= pressure drop due to weight of the packed bed

ΔP_w= pressure drop from friction at the wall, is comparatively smaller than ΔP_S because of the large wall surface and the fluidizing air further reduces the friction at the wall

ΔP_f= Pressure drop due to weight of fluid in bed. As a result of vast difference in density pressure drop due to the fluid is negligible when compared to the packed bed.

From the above and Bernoulli equation, total pressure drop may be written as

$$\Delta P = \Delta P_S = (1-\varepsilon_{mf})h_b\rho_p g \qquad (1)$$

Where, ε_{mf} = is void fraction, typical value for sharp sand is 0.4 [6].
Pressure drop across the distributor plate

$$\Delta P_d = 1/30 \times \Delta P \qquad (2)$$

U_{or} exit velocity through the orifice (radial holes) could be evaluated as

$$U_{or} = \left(\frac{2\Delta P_d}{\rho_f}\right)^{1/2} C_d \qquad (3)$$

Using Wen and Yu (1966) correlation [6]

$$Re_{mf} = \rho_f U_{mf} d_p/\mu_f = 33.7(1 + 3.59x10^5 Ar)^{0.5} \qquad (4)$$

Where A_r = Archimedes Number

But fluidizing air flow-rate is constant
Therefore, $\pi/4 U_{mf}\Phi^2 = \frac{\pi}{4} d_o{}^2 U_{or} N_{or}$ (5)

Using equation 1 to 5 with the following assumptions
a)fluidizing air enters the inert bed at 473K,
b) bed temperature during combustion is 1023K,
c) ρ_p =1600kg/m³ [13],

N_{or} is calculated as 300holes, with d_o = 1.5mm.

BIOMASS FEEDER

Biomass feeding unit essentially comprises of the Feed hopper, screw conveyor, and the low speed / high torque motor.

Screw conveyor:

For a screw conveyor according to [8] Quantity of material transported per hour Q (equivalent to f_d) may be written as

$$Q = 15.\beta.\pi.D^2.P.N\gamma K \qquad (6)$$

To achieve the proposed feed rate a small screw is definitely needed, hence a screw of diameter Dr= 5cm and pitch (p)=2.5cm was considered. The challenge then remains calculating the appropriate RPM.

From the literature ([8],[9]) the following assumptions were made.

β=0.4, since the material to be transported (PKS and CS) are light and non abrasive. (7)

k=1, since our conveyor is horizontal, the angle of inclination is 0^0 (8)

7 and 8 in equation 6 yields

$$Q = f_d = 1.061N \qquad (9)$$

Substituting f_d the desired speed range is obtained as

Nmin = 3.77 RPM
Nmax = 5.66 RPM

An infinitely variable-speed gear motor with output speed 8-38rpm was used, chain drive allowed reductions to the desired speed range.

GAS CYCLONE

Gas cyclone is the obvious choice for separating particles from BFBC exhaust, because of its effectiveness at extreme temperature, simplicity of construction, absence of any moving parts[10] and consequently low maintenance cost.
The characteristics of a suitable gas cyclone for the BFBC were evaluated as follows.

1. Litch Mathematical model based on turbulent flow with lateral mixing was used for calculation of the collection efficiency.
2. Stairmand cyclone configuration was selected for the Design (see fig 2).
3. The particulate loading of the flue gas in g/m³ was determined.
4. Diameter (D) of the cylindrical part of the cyclone was chosen as 200mm.

According to Leith and Litch [11],[12], Collection efficiency of a cyclone may be expressed as;

$$\eta_j = 1 - \exp[1 - 0.693\left(\frac{d_{pj}}{d_{p50\%}}\right)^{\frac{1}{(n+1)}}] \qquad (10)$$

Where

$d_{p50\%}$ = Paricle size with collection efficiency equals 50%

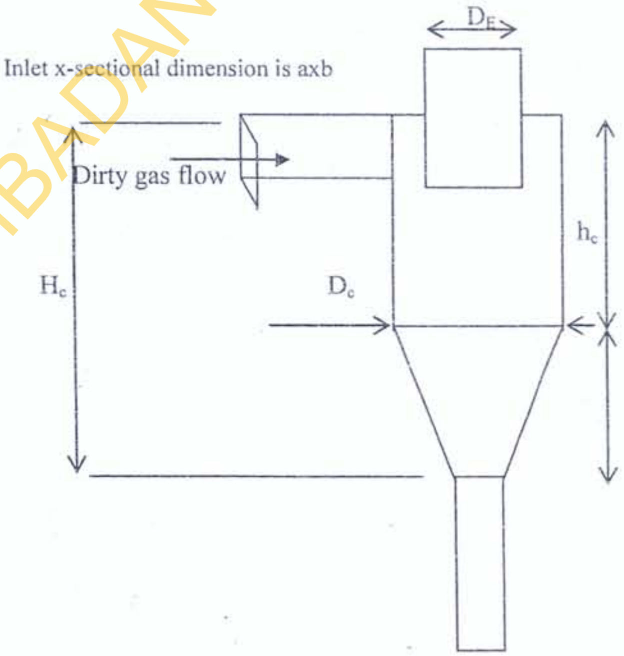


Fig 4: Schematic of Stairmand Cyclone

d_{pj} =particles size with collection efficiency other than 50%

$d_{p50\%}$ is evaluated as

$$d_{p50\%} = (\frac{0.693}{A})^{n+1} \qquad (11)$$

A is calculated as

$$A = 2[\frac{KQ\rho_p(n+1)}{18\mu D^3}]^{\frac{1}{2(n+1)}} \qquad (12)$$

n (vortex exponent) and k are emprical constants, for stairmaid configuration, n=6.4, k =551.3.

Q is the volume flow rate, D_c is cyclone cylindrical diameter, and μ is gas viscosity at temperature in cyclone seperator.

With the considerations of stairmand configuration other physical dimensions of the gas cyclone was calculated as below [12].

Since D_c =0.2m, for stairmand cyclone the following relations hold

Cyclone Height, H_c= 4*Dc = 0.8m

Height of cylinder, h_c=1.5Dc= 0.3m

Particulate exit, Bc=0.375Dc= 0.75m

Flue gas exit, D_E=0.5Dc= 0.1m

Width of gas inlet, a=0.25Dc= 0.5m

Height of the gas inlet, b=0.5Dc= 0.1m

THE OPERATING CONDITIONS OF THE GAS CYCLONE WERE EVALUATED AS FOLLOWS;

For maximum feed rate f_d=6kg/hr, 180g/hr of Ash will be generated with the flue gas stream. Fly ash value is a fraction of the total ash generated; typical value is 60-70%.[15]. Fly ash is expected to be the major particulate that will be collected at the gas cyclone.

Q (Volume flow rate of the flue gases) = mass flow rate of gaseous compt./density

But, Mass of flue gas = mass of the gaseous components + Mass of the particulate.

Mass of flue gas = mass of fluidizing air + mass of fuel

Therefore, maximum mass flowrate (f_d=6kghr^{-1}) = 80kg+6kg

It is assumed that, density of flue gas=0.746kg/m^3 at 200°c

Hence Q (Volume flowrate) =116.603m^3/hr

From the above and equation (12);

$$A = 2\left[\frac{[551.3X0.0324X0.61X7.4]}{18X0.2^3X2.286X10^{-5}}\right]^{\frac{1}{2[6.4+1]}}$$

$$= 10.071$$

μ (Air dynamic viscosity at 200°c) = $2.286X10^{-5}$ kg/ms [7]

Using the above, $d_{p50\%}$ is evaluated.

Subtituting all in equation 10, with focus on calculating $\eta_{(25\,\mu m)}$

$\eta_{(25\,\mu m)}$ = 75.4%.

In view of this reasonable efficiency, and bearing in mind that other possible particulates (elutriated bed materials, unburnt fuel particles) are generally larger in size than 25μm, it was concluded that the designed gas cyclone is appropriate.

So a Stairmand type gas cyclone with Diameter Dc =200mm was employed for the BFBC.

FABRICATION AND ASSEMBLY OF PARTS

The combustor body is made from 150mmx2900mm type 304 stainless steel pipe. The body is in modules, each module has 2 flanges machined with projection that match exactly with recess on the adjacent flange.

The base module is closed at one end by means of carbon steel plate(400mm x 200mm x10mm); which is joined to the foundation frame by 4 M10-6H bolts

The Distributor plate is sandwiched and effectively locked in place by the base module and the lower end of the second module

The second module dimension (diameter 150mm x 850mm) has openings and attachments for the biomass feeder, the propane gas inlet and the top and the bottom ash ports and Fluidizing air preheating. It also has 2 ports each for thermocouple and pressure manometer.

The Third and fourth modules are exact replica of the second however they have only the thermocouple and manometer ports.

The 5th and the topmost module diameter 150mm x 150mm, has one flange and is covered at the other end. It bears the opening for the flue gas and the attachment via which the Gas cyclone separator is coupled to the Main body.

Lagging is done with fiberglass insulation held in place by 0.5mm galvanized steel sheets, the thickness of the insulation comes to 70mm taking the outer diameter of the combustor to 296mm.

The combustor body is designed to be divided into 2 sections. The Lower section (module 1&2) and upper section (module3,4&5). Each section is properly tightened for rigidity and to prevent leakages. The Top of lower section and bottom of upper section has hinges which allows opening of the upper section for the purpose of viewing the fluidization of the bed at start-up or when need be.

A thermocouple placed at the entrance to the gas cyclone measured the flue gas temperature (T9) while on line gas analyzer probe is connected to a port on the flue gas outlet of the gas cyclone.

The centrifugal blower and biomass feeder are positioned on the base frame as shown in fig. 5 The base frame is constructed from welded 45mm carbon steel angle.

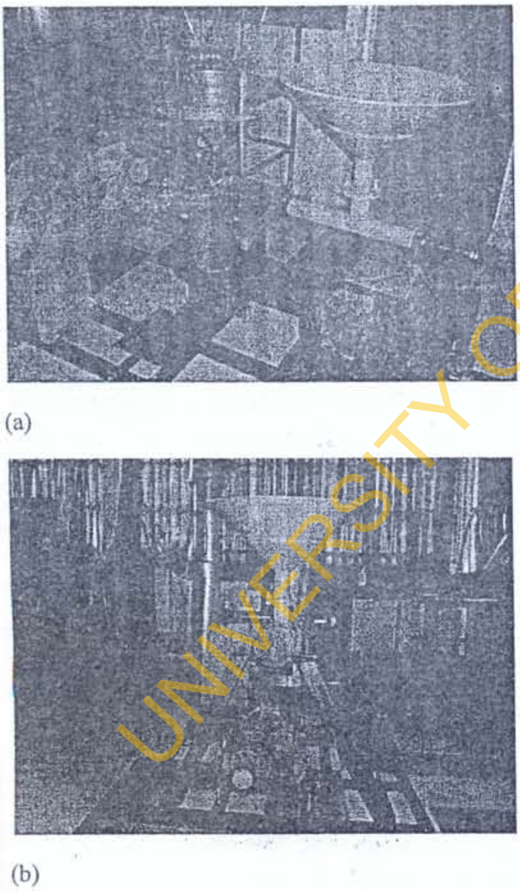


Fig 5: *(a)Picture of the BFBC showing the lower section, the biomass feeder to the right, and centrifugal blower to left all tightly fastened to the base frame, (b)shows a side view of the BFBC, the upper section of the combustor could be seen at the background.*

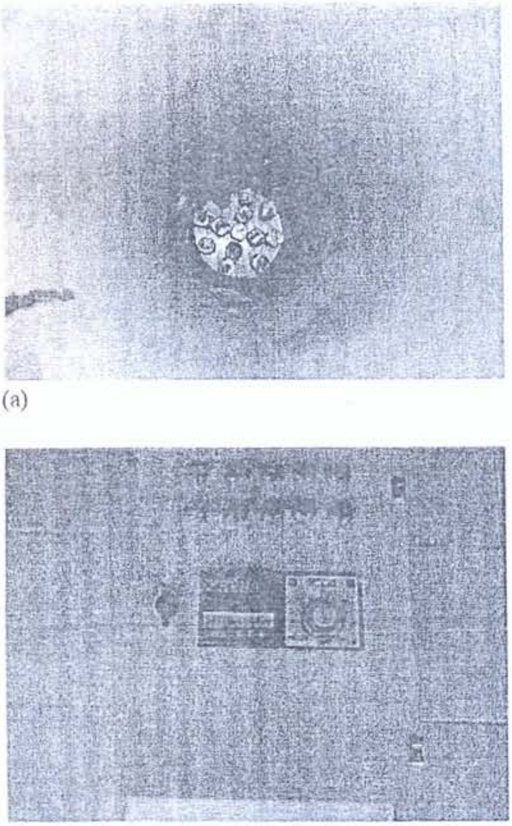
The control panel is located on the operator side of the BFBC and it house one microcomputer based digital temperature controller XMT*-808 series which sense the temperature via 8 thermocouples placed on the combustor. A Hartmann & Braun AG Temperature controller with analogue display is dedicated to monitoring the inert bed temperature. The H&B AG controller with a fabricated electronic feedback system (inert bed temperature regulating unit) ensure the bed temperature could be fixed to a particular value thus eliminating needs for cumbersome water cooling coil. The control panel also has 8 normally-open push button switch, each connect a thermocouple for zone(2 – 9) to the XMT*808 digital TC and upon closing the current temperature of each Zone could be read.

OPERATION AND TESTING OF THE BFBC

With all the auxiliary components properly attached the centrifugal blower was switched on. The Gate Valve was gradually opened until small occasional bubbling was noticed on the surface of the inert bed material (sand particles); this signifies the start of bubbling stage and corresponds to sudden but slight drop in manometer reading. The air flow-rate was further increased to ensure more turbulence, the propane gas valve was gradually opened until the inert bed catches fire from a torch. At this point the upper section is positioned and securely tightened by means of 6 M10-6H stainless steel bolt.

When the H&B AG controller indicated that the temperature of the bed has reached 500°C, the Biomass feeder was switched on to start the combustion process, and then the propane gas was switched off.

After the start-up, fluidizing air flow rate and the fuel were gradually increased to ensure stable combustion



(a)

(b)

Fig.6: (a)A view of inside of the BFBC, (b)shows the control panel with 2 temperature controller and 10 normally-off push button (2 inactive).

The first test-run was done with PKS with biomass feeder motor speed, N=15rpm. At this speed the consumptions was found to be 4.2kg/hr. The inert bed temperature was held steady at 800°C.

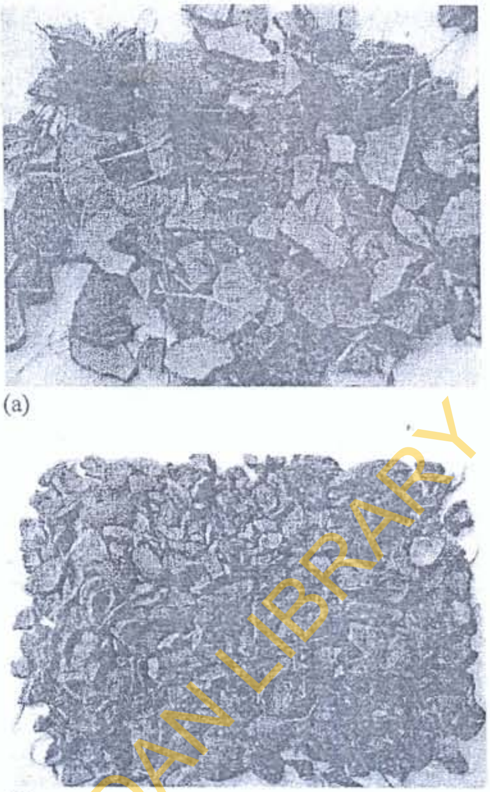
During the testing of the BFBC, following measurement were taken

i. the axial temperature along the combustor using Type K thermocouple

ii. The biomass consumption (kg/hr) for each run was evaluated from the mass of the biomass used and the time it takes to consume it. 4 test-run were done.

FUEL TESTED

The BFBC was tested with 3kg per batch of 'as received' palm kernel shell (PKS) and 3kg of pulverized coconut shell. The average size of the PKS varied from 4mm-19mm, the coconut shell varied in size from 4-16mm. The proximate and ultimate analyses were stated earlier in page 3.



(a)

(b)

Fig. 7: (a)Coconut shell sample (b)PKS sample

RESULTS AND DISCUSSION

With both fuels, stable combustion was achieved for all the test runs and all the zones show rapid increase in temperature until the inert bed temperature reached the pre-set temperature of 800° C the thermal profile is noticed to be in good agreements with what is seen in literature, the temperature fairly constant at 800°C from inert bed to the fourth thermocouple (T4) located 125mm above the distributor plate. Further up T5, T6, T7, T8 shows gradual decrease in temperature and T9 indicated the inlet temperature to the gas cyclone as 320°C, see fig 8.

EFFECT OF FEED RATE ON THERMAL PROFILE

For the second run the biomass feeder motor speed was increased, combustion of PKS at this speed for 1hr gives a feed rate of 5.2kg/hr. The new feed rate as expected had no effect on the inert bed temperature, since this was already pre-set, freeboard temperature however was noticed to be significantly higher with T9 moving from 320°C to 422°C. This could be explained by the fact that higher f_d implies higher volatile combustions in the freeboard and consequently the higher value observed for T4, T5, T6, T7 & T8. See fig 6. A similar result was obtained with CS. It was also observed that the frequency at which the biomass feeder is switched-on and off by the inert bed temperature regulating unit increased markedly with the f_d =5.2kg/hr.

Analysis of flue gas composition was not done in this experiments however the flue gas was observed to be clean and transparent in all the tests run done.

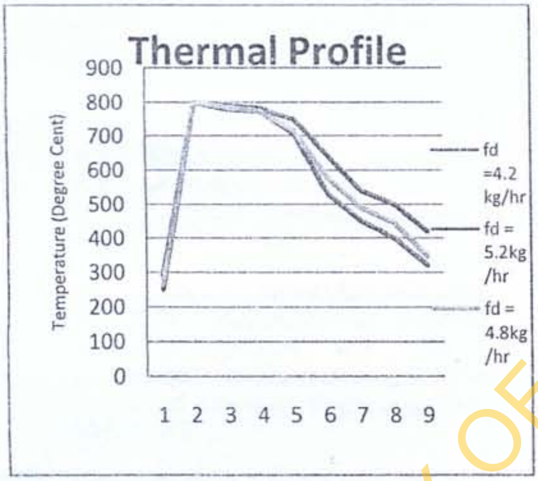


Fig 8: A plot of thermal profile against the height above the distributor plate(Represented as thermocouple Zone, Zone 1 represents base of the distributor plate while Zone 9 is exhaust). Uniformity of temp in Zone 1 and Zone 2 is an indication of effectiveness of inert bed temperature regulating unit. The significant thermal difference obtained at exhaust (Zone 9) is an indication of higher volatile combustion in the freeboard for f_d = 5.2kg/hr.

CONCLUSIONS

The developed BFBC was used to successfully fire 'as received' PKS and pulverized CS. The effectiveness of the inert bed temperature regulating unit shows that the problem of de-fluidization resulting from ash fusion in the inert-bed could be eliminated since the unit ensured that the inert bed temperature is maintained at the pre-set value in all the tests done.

Since Nigeria has no experience with fluidized bed combustion of biomass, success with the developed BFBC could be applied to building experimental models and commercial size BFBC for the purpose of utilizing the abundant biomass resources in this country and its environ for decentralized renewable energy generation.

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