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Fluidised Bed Combustion: Towards Alternative Ways of Energy Recovery in Rural Nigeria

Professor C. O. Folayan[1] Dr. G.Y. Pam[1] Yusuf Bello Habib[2*]
1.Department of Mechanical Engineering, Faculty of Engineering, Ahmadu Bello University
2.Department of Energy Management, Training and Manpower Development, Energy Commission of Nigeria
*Email of corresponding author: yusuf_bello18@yahoo.com

Abstract
Modern energy poverty in rural Nigeria has been an on-going problem for decades. Over half of Nigeria's population is estimated to be in the urban areas, with less than 40% of the rural community connected to the national grid partly due to high cost of rural electrification exercise. Hence the rural population continuously rely on direct burning of solid biomass (like fuel wood) as means of obtaining much needed energy for basic applications like cooking and heating. This *collect and burn* process consequently contributes to environmental concerns like climate change, acid deposition, environmental health and, deforestation, which has been identified as one of the leading causes of soil degradation. As the concept of sustainability shapes the fabric of the modern society, it is necessary to explore environmentally friendly methods of extracting biomass energy for rural use. One such means is energy recovery using fluidised bed combustors. This system uses agricultural waste as fuel source to produce heat energy for light load applications. The objective of this document therefore is to discuss the design and construction of a maize cobs fluidized bed combustor. Test results recorded high flue gas and bed temperatures of over 300˚C and 850˚C respectively, suitable for rural application including grain drying and water boiling.
Keywords: Fluidise, maize, temperature, energy, flue gas

1.0 Introduction

Global demand for electricity has led to rapid depletion of non-renewable energy resources (fossil fuels). This demand, along with crude oil prices are key factors driving renewable energy development and utilisation (A. Galadima *et al*., 2011).

Renewable energy is the energy which comes from natural sources such as the sun, wind, water and plant or animal organic matter. It is recovered by natural processes at a rate equal to or faster than the rate at which it is consumed.

As one of the dominant renewable energy sources in the world, biomass can be converted to bioenergy either by combustion, gasification, conversion of biomass to biofuels or biomass briquettes. However, the process of direct combustion accounts for the majority of the energy generated from biomass especially in developing countries where it provides basic energy for cooking and heating in rural households (ECN, 2006).

Biomass is also extensively utilized in sub-saharan African countries like Nigeria where 80% of the biomass energy consumed is obtained from fuel wood and charcoal (Ojo and Chuffor, 2013). Although the use of wood fuel is relatively cheap in this part of the world, deforestation has been identified as one of the leading causes of land degradation in impacted communities (IFAD, 2001). Direct combustion of wood fuel also leads to general environmental problems including climate change and acid deposition, due to the emission of gases like carbon dioxide, sulphur and nitrogen oxides. It is therefore possible to reduce the excessive use of fuel wood by introducing crop residue as an alternative source of energy.

Every year, a significant volume of biomass in the form of agricultural waste is generated within the rural areas of Nigeria. The waste is a potential source of fuel for heat and power generation, and hence, the energy that could be generated is wasted by indiscriminate dumping and burning (Theresa I. and Omotayo S., 2013).

Globally, agricultural waste has been used in small scale power plants for electricity generation. In India for example, rice husk has been used to generate upto 7.7MW of electricity using a steam turbine at Bilaspur (VVL, 2007).

Since connection to the national electrical grid is a rare occurrence in rural areas of the developing world, localized grid can be established using a local power source such as agricultural waste. Individual households can also be connected to standalone systems which are powered by any of a wide variety of energy sources.

There are several benefits of introducing electricity to rural communities. While obvious reasons include social gains like lightening, cooking and water pumping, electricity will help to stem the flow of rural-urban migration which is a common problem in many developing countries like Nigeria. Introduction of electricity also helps to provide productive employment in rural areas thereby creating a positive impact on economic as well as social growth.

Fluidised bed combustion will provide efficient and affordable source of energy thereby boosting rural education and development. Hot flue gases generated can also be used for low temperature applications like grain drying. The technology has high greenhouse gas mitigation potential since it uses renewable fuel and eliminates sulphur and nitrogen oxide emissions during combustion, thereby curbing global warming and acid deposition.

2.0 Principle of Fluidisation

When an upward flowing gas moving with a certain velocity is passed through a static bed of particles, then the particle will be partially suspended once the gas velocity reaches a certain minimum fluidization velocity (Gadgil R.P., 2009). Hence the minimum fluidization velocity is the velocity required to move the static bed, in other words, the velocity necessary to begin fluidization. The quality of fluidization obtained varies from one bed material to another, and intrinsic properties including particle density, particle size and surface characteristics definitely affect the outcome of fluidisation (Johari and Taib, 2007).

Combustion temperature is maintained below 1000ºC to minimise NOx formation, and bed materials like lime stone serve to control SOx emissions, eliminating the need for scrubbers.

The operating velocity of the fluidized bed must be maintained between the minimum fluidization velocity and the terminal velocity, the maximum gas velocity beyond which particles will be entrained.

3.0 Bubbling Fluidized Bed Combustors

The design of the fluidised bed system using agricultural waste as fuel consists of three units. These are the main combustor or fluidised bed column, the distributor plate and the cyclone separator.

The fluidised bed combustor contains sand as the bed material and is capable of burning a wide range of fuel to generate heat energy. Air from the force draft fans or blower is supplied into the fluidised bed column. The air passes through holes in the distributor grid, lifting the bed material. This makes the sand particles behave like a fluid. The solid fuel (biomass feed) is then introduced into the bubbling bed and is immediately burned as the bed is agitated. Hot flue gases generated during combustion flow into the cyclone where the combustion gas and entrained solids are separated. The temperatures of the bed and flue gas are then measured using the thermocouple wire to determine its suitability for thermal application. Fig. 3.0 shows a schematic of the fluidised bed model.

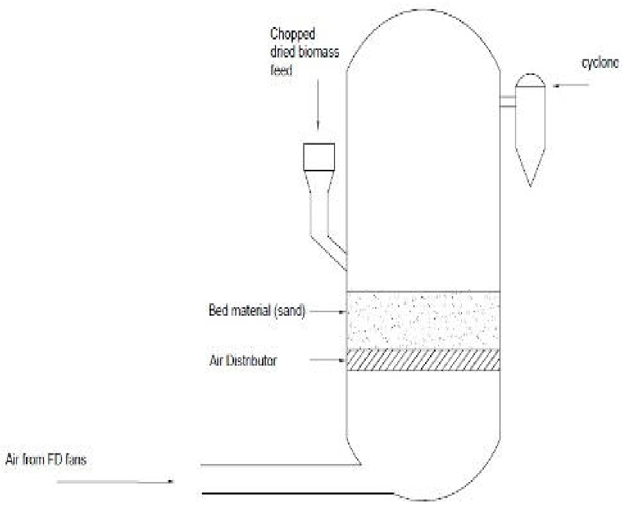

Fig. 3.0A schematic of the fluidised bed model

4.0 Design Consideration

4.1 Calorific Value

The fuel has a significant effect on the design and operation of fluidised bed combustor. Fuels with higher reactivity have greater combustion efficiency. Previous studies show that the amount of combustible losses in the fly ash is inversely proportional to the heating value of the fuel (Basu, 2006).A maize cob with calorific value of 3850kcal/kg was considered in this design (UNEP, 2012).

4.2 Combustion Temperature

Typical combustion temperature for fluidised beds falls within the range of 800 – 900 degree Celsius (**Vos, 2005**). Although this temperature range minimizes the formation of sulphur and nitrogen oxides, higher temperatures will ensure reduced combustible losses in unburned fuel particles which escape through the cyclone with incomplete combustion. However, some biomass fuels like rice husk (which could be burned at temperatures as low as 600 – 700 degrees celsius) could attract value-added use for their ash when burned at low temperatures (Basu 2006).

4.3 Minimization of Combustible Losses

In fluidised bed combustors, the residence time of carbon particles is affected by the type of feed, particle size and fluidizing velocity. The residence time becomes shorter for particles with significantly lower terminal velocities, favouring high percentage of unburned carbon in the fly ash. Therefore, a lower operating velocity must be selected for the combustor in such cases.

4.4 Gravity chute feed hopper

A gravity chute is a simple device where biomass fuel is fed into the bed via a chute which functions with the help of gravity. The absence of moving part makes it suitable for rural application, where routine maintenance may not be forth coming. Since the fuel is not well dispersed, much of the volatile matter is released near the outlet of the feeder, which causes a pressure surge and a reducing atmosphere. Due to reasons, fine fuel particles like rice husk might be blown back into the chute while reducing conditions encourage corrosion.

4.5 Bed Material and Bed Height

Since the size of bed material influences fluidisation quality, sand particles with mean size and density of 220µm and 1602 kg/m^3 respectively was adopted. Concerns have been raised regarding the accuracy of calculations used in bed height design, and empirical relations do not yield good results (Thermopedia, 2010). Consequently, bed height of 300mm is used throughout this work.

4.6 Power Requirement

The suggested horse power requirements for different flow types and operations are in table 4.6.

Table 4.6.: Fluidisation fan power requirement for various operations

Type of flow	Power requirement (hp/1000 gal)	Types of operation
Mild	0.5 – 2	Mixing, blending
Medium	2 – 5	Heat transfer, suspension, gas absorption
Violent	5 – 10	Reactions, emulsification

Source: (Oluleye A. E. et al., 2012)

5.0 Design Analysis

5.1. Bed Temperature, T_b

In Fluidised Bed Combustors, mean bed temperature in the range of 800^{o}C to 950^{o}C is ideal. This is because a higher bed temperature favours the formation of NOx pollutants. Bed temperature has enormous impact on pollution control and can be controlled by controlling the fluidizing air. Increasing the fluidizing air flow increases the bed temperature, and decreasing fluidizing air flow lowers bed temperature (Kraft, 1998). An Experiment on the combustion of residual oils in a fluidised bed of dolomite showed that combustion efficiency as high as 98% could be obtained at 850^{o}C (Morita *et al*, 1999).Furthermore, concentrations of SOx and H_2S as low as 10ppm were recorded under this temperature.

5.2 Bed Depth

The bed depth in almost all atmospheric fluidised bed combustors is usually 0.9m – 1.5m deep (UNEP, 2007). However, bed height as low as 400mm have been used for experimental purposes (Morita *et al.*, 1999). Since part load operations are usually considered in designing BFB boilers, heat absorption in the bed can be changed by adjusting the bed depth allowing load change of up to 5% per minute (Basu, 2006). Deeper beds give greater combustion efficiency since they provide longer residence time for combustion, consequently increasing the fan power requirement and entrainment rate of solids. Choices of fuel and combustion requirements are factors to consider when determining the bed depth (Basu, 2006).

5.3 Bed Material and Particle Size

Fluidisation largely depends on particle size and air velocity. Recent test suggests that sand particles of about 350µm give better bubbling compared with alumina abrasive and china clay (UNEP, 2007).

5.4. Minimum Fluidisation Velocity, U_{mf}

The minimum fluidizing velocity determines the beginning of fluidisation in a bed of particles. The minimum fluidizing velocity, assuming small spherical particles, is given by (Kunii and Levenspiel, 1991)

$$U_{mf} = \frac{(\emptyset_s d_p)^2(\rho_s - \rho_g)\varepsilon^3 g}{150\mu(1-\varepsilon)} \text{ ----------------------- (1)}$$

$Re_p < 20$

For large particles,

$$U_{mf} = \left[\frac{(\emptyset_s d_p)^2(\rho_s - \rho_g)\varepsilon^3 g}{1.75\,\rho_g}\right]^{1/2} \text{ ------------------ (2)}$$

$Re_p > 20$

5.5. Superficial Velocity, U

This is the operating velocity at which the fluidising gas is supplied to the fluidised bed combustor. The superficial velocity is selected between the minimum fluidising velocity and terminal velocity and hence, has no specific value. As a rule of thumb, the operating velocity is usually three to five times the minimum fluidisation velocity (Gupta and Sathiyamoorthy, 1999).

A comparison of the physical features of fluidised bed boilers with other types of boilers reveal that bubbling fluidised beds have a superficial velocity ranging from 1.5 – 2.5 m/s (Basu, 2006).

5.6. Terminal Velocity, U_t

In fluidised bed combustion, solids are generally retained within a certain height above the bed (Basu, 2006). Except for some entrainment, there is no large-scale migration of particles with the gas. This is because the superficial velocity of the particles is under the maximum fluidisation velocity, which is the terminal velocity. Hence particles with terminal velocity lower than the superficial velocity in the free board are carried away.
Mathematical expression of terminal velocity according to Kunii and Levenspiel (1991), is given by

$$U_t = \sqrt{\frac{4gd_p(\rho_s-\rho_g)}{3C_D\rho_g}} \text{------------------------------------- (3)}$$

Where C_D is the drag coefficient for spherical particles, and is given by (Basu, 2006)

$$C_D = \frac{a_1}{Re^{b_1}} \text{-- (4)}$$

Where the constants a_1 and b_1 can be approximated as given in table 5.6
Table 5.6 Approximation of constants a_1 and b_1 for different ranges of Reynolds's number

Range of *Re*	Region	a_1	b_1
0 <*Re*< 0.4	Stoke's law	24	1.0
0.4 <*Re*< 500	Intermediate law	10	0.5
500 <*Re*	Newton's law	0.43	0.0

Calculation of terminal velocity is interactive since Reynolds's number is a function of U_t and vice versa.

5.7. Gas Viscosity, μ

Viscosity is a property of the fluidizing gas (air) and is obtainable from appendix B which contains properties of air at atmospheric condition. However, mathematical expression for viscosity is available according to Subramani *et al.* (2007), and is given by:

$$\mu = \left[1.46(10^{-6})\left(\frac{T_b^{1.504}}{T_b+120}\right)\right] \text{------------------------- (5)}$$

5.8. Gas Density, ρ_g

Like viscosity, gas density is also available in appendix B. Gas density is a function of bed temperature according to Bird *et al.* (1960) and is expressed as

$$\rho_g = \frac{353.2}{\sqrt{T_b}} \text{------------------------------------- (6)}$$

5.9. Bed Voidage, ε

The bed voidage depends on a large number of factors, such as terminal velocity, type of
particles, vessel diameter, fluidisation regime, and fluidisation velocity. Fluidisation velocity is the one most affecting the voidage (Basu, 2006).
The value of ε for packed beds can be obtained from appendix A. Equation for bed voidage has also been recommended by Nag (2002) as

$$\varepsilon = 1 - \frac{\rho_b}{\rho_a} \text{------------------------------------ (7)}$$

Where ρ_b – bulk density
ρ_a – Apparent density
Generally, the voidage at minimum fluidizing conditions ε_{mf} may be assumed to be 0.45 (Karimipour, 2010). Attempts have been made to establish an empirical correlation of ε_{mf} as a function of Re_{mf} and Ar (Singh, 2008)

$$\varepsilon_{mf} = 0.3507Ar^{0.0387}Re_{mf}^{-0.0704} \text{----------------- (8)}$$

Where Ar is the Archimedes number given by

$$Ar = \frac{\rho_g d_p^3(\rho_s-\rho_g)}{\mu^2} \text{----------------------------------- (9)}$$

and

$$Re_{mf} = \frac{\rho_g U_{mf} d_p}{\mu} \text{---------------------------------- (10)}$$

5.10 Design of Gas Distributor

The primary combustion air enters the furnace through an air distributor. The distributor plate supports the bed materials and homogeneously distributes the fluidizing gas into the bed of solids. This is an important aspect of the design of fluidised bed because, beyond the distributor plate, there is no other physical means for influencing the distribution of air through the solids. Non-uniform distribution of air may result in a number of problems; from reduced performance of the combustor to complete collapse of the bed due to agglomeration.

5.11 Distributor Grids for Bubbling Fluidised Beds

A Bubbling Fluidised Bed boiler or gasifier uses a relatively coarse particle and low fluidizing velocity. If the fluidizing air above its grid is not uniformly distributed, the air velocity in one region could drop below the minimum fluidizing velocity of the coarser fraction of the bed materials. In a bubbling bed, the operating velocity is low (0.5 to 1.7 m/sec) but particle size is large (1 mm). Thus, the fluidisation number is low and its superficial velocity is not far from the defluidisation velocity of average particles. Due to this, a faulty distribution of air may take the bed close to defluidisation, which could eventually lead to clinkering. This and other issues make the design of distributor plates for bubbling fluidised beds rather critical.

For perforated distributors, important factors to consider are:

- Pressure drop across the grid, which should be 0.3 times pressure drop across the fluid bed

5.11.1 Diameter of the orifice

Pressure Drop, ΔP_b

At minimum fluidisation, pressure drop across the bed according to Kunii and Levenspiel (1991), can be expressed as

$$\Delta P_b = L(1-\varepsilon_{mf})(\rho_s-\rho_g)g \text{ ----------------- } (11)$$

5.11.2 Orifice Velocity, U_{or}

According to Werther and Karri (2003), the orifice velocity can be obtained from the orifice equation given by

$$U_{or} = C_d\sqrt{\frac{2\Delta P_d}{\rho_g}} \text{ ----------------------------------- } (12)$$

Where C_d is the coefficient of discharge

5.11.3 Orifice Number, N_{or}

For a selected orifice diameter, the orifice number according to Werther and Karri (2003) is obtained from the expression

$$U_{mf} = \frac{\pi d_{or}^2 U_{or} N_{or}}{4} \text{ -------------------------------- } (13)$$

5.12 Distributor Thickness

The flow through plates can be described theoretically by a wide range of models. For perforated plates however, the Hagen-Poiseuilles law can be used to describe the relationship between pressure drop across the distributor and superficial velocity (Nilsson, 2007).

$$\frac{\Delta P_d}{t} = \frac{32\mu U_{mf}}{d_{or}^2} \text{ ------------------------------------- } (14)$$

Where t is the thickness of the distributor

Some of the most important assumptions implied in the development of the Hagen-Poiseuilles law are that the flow in the channels is laminar, the density is constant and the fluid behaves as a continuum.

5.13 Plenum Chamber

The major advantage of plenum design is to achieve uniform pre-distribution of fluidizing gas before it passes the distributor grid. Different plenum designs have been proposed based on the location of gas entry into the fluidisation column. In order to ensure uniform distribution of the gas, the gas entry point must be separated from the distributor plate by a distance H_{plenum}. Litz (1972) assumed that a high velocity gas stream entering the plenum horizontally or vertically expands as a conical-free jet until it dissipates itself. He proposed the following correlations.

For horizontal gas entry,

$$D_{entry} > D_{plenum}/100 \qquad H_{plenum} = 0.2D_{plenum} + 0.5D_{entry} \text{ ----------- } (15)$$

$$D_{entry} < D_{plenum}/100 \qquad H_{plenum} = 18D_{entry} \text{ ----------------------- } (16)$$

For vertical gas entry,

$$D_{entry} > D_{plenum}/36 \qquad H_{plenum} = 3(D_{plenum} - D_{entry}) \text{ ------------ } (17)$$

$$D_{entry} < D_{plenum}/36 \qquad H_{plenum} = 100D_{entry} \text{ ------------------------ } (18)$$

5.14. Bed Expansion Design

When the superficial gas velocity is equal to U_{mf}, the minimum fluidisation velocity, there are no bubbles, and only emulsion phase remains. However, for Group B and D particles, further addition of any gas triggers the formation of bubbles, which push their way into the emulsion phase of solids, resulting in bed expansion. The following is an expression for bed expansion, assuming the bubble velocity to be constant at a mean value of U_{bm} as derived by Davidson and Harrison (1963).

$\frac{H-H_{mf}}{H_{mf}} = \frac{U-U_{mf}}{U_{bm}}$-------------------------------------- (19)

5.15 Bubble Velocity, u_b

A single bubble rises through the emulsion phase with a velocity (Kunii and Levenspiel, 1991):

$u_{bs} = 0.711\sqrt{gd_b}$----------------------------------- (20)

The above velocity of bubbles is not the absolute velocity; it is with respect to the emulsion phase.

When a new bubble enters the bottom of the bed, it pushes up the emulsion phase by a volume corresponding to its own. Thus, the emulsion phase itself rises up with an absolute velocity$(U - U_{mf})$up to the bed surface. The absolute velocity of the bubble,$U_b$is (Kunii and Levenspiel, 1991):

$U_b = (U - U_{mf}) + u_{bs}$ ---------------------------- (21)

5.16 Bubble Diameter, d_b

In BFB, the amount of gas passing through the emulsion phase is equal to that required for minimum fluidisation, AU_{mf}. Therefore, the remaining gas, $A(U - U_{mf})$ passes through the bubble phase. The equivalent volume diameter d_b, of a bubble at a height Z, above the distributor is a function of the nozzle area of the distributorA_o, and the superficial gas velocity through the bubble phase$(U - U_{mf})$. Calculation for bubble diameter can be expressed using the equation given by Darton *et al.* (1977) as:

$d_b = 0.54(U - U_{mf})^{0.4}(Z + 4\sqrt{A_o})^{0.8} g^{-0.2}$----- (22)

Where g is the acceleration due to gravity in m/sec^2

Mori and Wen's (1975) developed a method for group B and D particles. In this method, the expression for d_b is as follows:

$d_b = d_{bm} + (d_{bo} - d_{bm})exp\left(-\frac{0.3Z}{d_t}\right)$ ----------- (23)

Where

$d_{bm} = 0.65[A_o(U - U_{mf})]^{0.4}$ -------------------- (24)

$d_{bo} = \frac{2.78(U-U_{mf})^2}{g}$ - ------------------------------- (25)

and

A_0 = area of the grid per orifice

Note that U and $U_{mf}$are in cm/sec and A_o is in cm^2

5.17. Volume Fraction of Bubbles in the Bed,ε_b

The following continuity equations are used to calculate the volume fraction of bubbles in the bed according to Fogler and Brown (1981),

$1 - \varepsilon_b = \frac{1-\varepsilon}{1-\varepsilon_{mf}} = \frac{H_{mf}}{H}$---------------------------- (26)

Or

$\boldsymbol{\varepsilon_b} = \frac{U- U_{mf}}{u_b- U_{mf}(1+\alpha)}$--------------------------------- (27)

5.18 Transport Disengagement Height (TDH)

Beyond a certain height, only a negligible amount of particles disengage from the gas to return to the dense bed. This height is known as transport disengaging height (Fig. 5.18). Beyond this height, only particles whose weight is sufficiently small to be balanced by the fluid drag are carried up.

More specifically, particles with terminal velocities lower than the superficial velocity in the freeboard are carried away. The flux of particles carried away beyond the TDH is known as the elutriation rate. Numerous research has been done in an effort to evaluate the TDH. Amitin *et al.* (1968) proposed an empirical correlation for the TDH taking the superficial velocity, U, and the acceleration due to gravity,g into account.

$TDH = 1.08U^{1.2}(6.71 - 1.21gU)$--------------- (28)

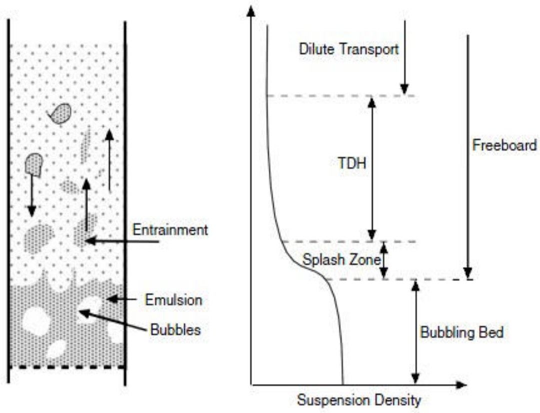

Fig.5.18. Bubbles erupt on the surface of a bubbling bed ejecting solids which travel up through the freeboard. The solid concentration reduces along the height but remains unchanged beyond the TDH.

5.19 Cylinder Thickness

A cylindrical pressure vessel is classified as thick or thin walled based on its thickness to radius ratio. Hence for thin walled cylinders (Den Hartog, 1952),

$$t/r \leq \frac{1}{10} \quad (29)$$

For thick cylinders,

$$t/r \geq \frac{1}{10} \quad (30)$$

5.20 Insulation Thickness

One of the primary purposes of insulation is to conserve energy and minimize financial and thermal loses. In a cylindrical piece, additional insulation increases the conduction resistance of the insulation layer but decreases the convection resistance of the surface because of the increase in the outer surface area for convection. The heat transfer from the pipe may increase or decrease, depending on which effect dominates.

Consider a cylinder of outer radius r_1 whose outer surface temperature T_1 is maintained constant. The cylinder is now insulated with a material whose thermal conductivity is *k* and outer radius is r_2. Heat is lost from the cylinder to the surrounding medium at temperature T_2, with a convection heat transfer coefficient *h.* The rate of heat transfer from the insulated cylinder to the surrounding air can be expressed as (N.B.Totala *et al.*, 2013)

$$q_r = \frac{(T_1 - T_2)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} + \frac{1}{h(2\pi r_2 L)}} \quad (31)$$

Where L is the length of the cylinder

Hence the value of r_2 (the critical radius) at which heat transfer rate reaches maximum is determined from the requirement that $\frac{dq_r}{dr} = 0$

5.21. Entrainment

5.21.1 Design of Cyclone

Cyclones are always an essential part of fluidised beds. The absence of moving parts, simple construction, and high efficiency make a cyclone especially suitable for FB combustors.

The most common cyclone design has a tangential inlet, consisting of an upper cylindrical part referred to as Barrel and a lower conical part referred to as cone

There are different cyclone configurations which include 1D2D, 2D2D and 1D3D. However, previous research by Wang (2000) indicated that, compared to other cyclone designs, 1D3D and 2D2D are the most efficient cyclone collectors especially for fine dust (particle diameters less than 100 µm). Hence in the scope of this work, the 2D2D configuration will be adopted. This configuration is shown in fig. 3.4.21.2

5.21.2 Cyclone Diameter, D_c

The cyclone diameter D_c as defined by Kalen and Zenz's model is given by

$$D_c = 0.0502 \left[\frac{Q\rho_g^2(1-K_b)}{\mu\rho_p K_a K_b^{2.2}}\right]^{0.454} \quad (32)$$

Where D_c is the optimum cyclone diameter (ft), Q is the gas flow rate (ft^3/sec), ρ_g is the gas density (lb/ft^3), µ is the viscosity (lb/ft.sec), ρ_p is the particle density (lb/ft^3) and K_a and K_b are design parameters.

- **2D2D Cyclone Dimension Correlations**

$B_c = \frac{D_c}{4}$ -- (33)

$D_e = \frac{D_c}{2}$ -- (34)

$H_c = \frac{D_c}{2}$ -- (35)

$J_c = \frac{D_c}{4}$ -- (36)

$L_c = 2xD_c$ -- (37)

$Z_c = 2xD_c$ -- (38)

$S_c = \frac{D_c}{8}$ -- (39)

6.0 Ignition/Testing Procedure

The system was assembled outside the boiler room, mechanical engineering departmental workshop, ABU Zaria. The bed material (sand) was prepared by removing larger particles which can potentially affect the quality of fluidisation using a sieve. The bed material was then poured over the distributor grid. A shallow bed of 150mm was maintained in this case owing to the size of the sand particles.

The three-phase constant speed blower used during this test was converted to a single-phase blower with the help of a 50 microfarad capacitor.

To initiate combustion, a small amount of charcoal, sprayed with kerosene was spread evenly across the bed before being ignited with matches. The charcoal was allowed to burn for about 2 to 3 minutes to allow heat to penetrate some parts of the bed, before the blower was switched-on.

The combustor was then enclosed with the feed-hopper, and the agricultural waste (mostly maize cobs) was supplied at a rate of 5 kg/h manually.

6.1 Bed Temperature

The temperature of the bed immediately after ignition was initially measured to be 29 °C. The bed temperature rose proportionally with time, reaching 853 degrees Celsius in 25 minutes as shown in table 6.1. The MASTECH multipurpose clamp meter is the instrument used to carry out temperature measurements in this work. It is basically a digital multimeter which uses the k- type thermocouple wire to measure and display temperature readings directly in degree celsius on its display screen

Table 6.1: Bed temperature rise with time

Time (min)	Bed Temperature (Degree Celsius)
0.0	29
5	109
10	231
15	576
20	638
25	853

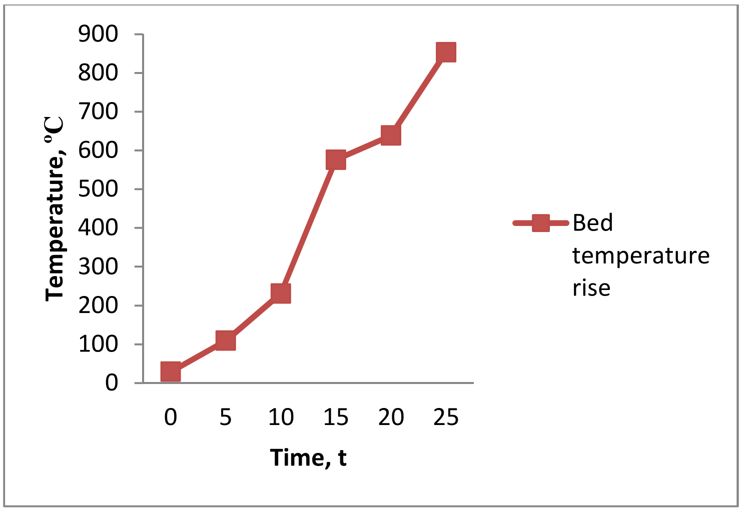

Fig.6.1: Rise of bed temperature with time

6.2 Flue Gas Temperature

The temperature of the flue gas was also measured using the k- type thermocouple wire accessory of the

MASTECH digital multimeter. The measurement was carried out after thirty minutes of normal operation of the fluidised bed combustor. During measurement, the flue gas temperature rose sharply to over 300 °C in 5 minutes. The result is shown on table 6.2.

Table 6.2: Flue gas temperature rise with time

Time (mins)	Flue gas temperature (degrees Celsius)
1	44
2	128
3	264
4	353

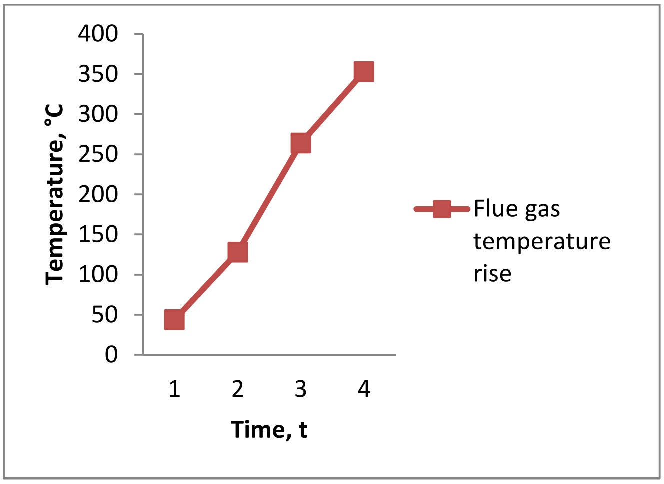

Fig.6.2: Flue gas temperature rise measured after 30 minutes of operation

7.0 Result Discussion

Bed temperature is an important property considered in fluidised bed combustors. Table 6.1 shows that the system can produce temperatures as high as 850 degrees Celsius. However, the bed temperature has the tendency to rise beyond the measured values over prolonged periods of operation especially during co-combustion, where the agricultural waste (maize cobs) is burned along with high carbon fuels like coal. In some cases, agglomeration occurs in the bed causing the bed material to fuse and form a lump mass. This often leads to total collapse of the bed, thereby affecting the performance of the combustor.

The combustion of maize cobs (Plate 7.0) shows that the obtained bed temperature is adequate for utilizing the chemical energy contained to produce the desired heat output.

Plate 7.0: Burnt maize cob samples

The char obtained after the combustion of maize cobs can be converted to briquettes for use in advanced cooking stoves.

Table 6.2 presents the temperature in degree celsius obtained from the flue gas. Although the temperature obtained is as high as 300 °C, the amount of energy obtained from the flue gas will largely depend on the efficiency of the heat exchanger, through which this energy can be transferred for some light load applications.

The flue gas contains enough heat energy for low energy applications like pre-heating and drying which require minor heat workouts. The temperature may not be sufficient for high energy applications especially where the point of application is farther away from the heat source (Combustor).

Temperature values of 115 °C and 63 °C have been used by Soponronnarit S. (1999) and Oluleye A. E *et al.* (2012) respectively for grain drying purposes, with the latter recording drying efficiency as high as 89% for rice and wheat grains.

Generally, the designed fluidised bed combustor has been successful because the operating/bed temperature of the system is high enough for steam generation and the flue gas temperature is adequate for low-heating applications. In terms of fluidisation quality, the designed combustor recorded mixed results ranging from partial to near complete fluidisation of the bed. The partial fluidisation can be attributed to the fact that different categories of bed materials (sand) were used over different test periods.

It is important to note that the heat generated within the combustor must be continuously extracted out of the system. Since testing was done under no load conditions, the test period was limited due to risk of overheating.

7.1 Energy Potential in Maize Cobs

According to a report by National Agricultural Extension and research Liason Services and National Food Reserve agency of federal ministry of agriculture and water resource, 1,027,790tonnes of maize was produced by Kaduna State in 2009.While adopting a stover to grain ratio of 1:1, maize cobs make up to 15–20% of maize stover (Zych, 2008). Hence, based on 15-20% stover that is maize cobs, an estimated 154,000 – 205,000 tonnes of maize cobs was produced in Kaduna State.

If we consider 154,000 tonnes/y of maize cobs produced in Kaduna state in 2009, then the amount of maize cobs produced per hour is 18 tonnes/h.

1kcal/kg = 4.1868 kJ/kg = 0.004183 MJ/kg

Therefore, the calorific value of the fuel, 3850kcal/kg (maize cobs), can be re-written as 16.12 MJ/kg or 16120 MJ/tonne. Since 18 tonnes/h of waste was generated in 2009, the corresponding energy content of 290160 MJ/h or 80.6 MJ/s could be obtained. This implies that 80.6 MJ/s of energy for heating is available from maize cobs generated in Kaduna state alone in 2009.

However, less than 60% of energy in a fuel is converted to power, with average efficiency of around 33% for centralised power systems (Wade, 2014). Generally, electrical generating efficiencies of 36% for large utilities and just 10% for small utilities are typical of steam turbine plants (ICF Inc., 2008). Adopting 10 – 36% conversion efficiency, 8.06 MW – 29.02 MW of electrical power is obtainable from maize cob waste generated in Kaduna state.

Since the fluidised bed combustor can accommodate fuel feed rate of 5 kg/h, the total heating energy obtainable, using 16.12 MJ/kg heating value is 0.022 MJ/s. Consequently, electrical power output of the system should be within the ranges of 2.2 kW – 7.92 kW. For a system scheduled to operate for 4000 hours in a year, energy consumption of 8800 kWh – 31680 kWh could be recorded.

The fluidised bed combustor can help farmers and villagers harness some of this energy through more efficient combustion in order to arrest energy demand problems plaguing rural Nigeria.

8.0 Recommendations

The following recommendations are proposed to improve the fluidised bed combustor.

- Since the pressure of the system is higher than the atmospheric pressure, light weight fuels like rice husk and groundnut shells will be blown out of the feed hopper. It is therefore necessary to modify the feed hopper to accommodate fuels of all sizes.
- The temperature in the fluidised bed column has the tendency to rise significantly, especially during no-load conditions. This in-turn can have adverse effects on insulation material, and hence, the need to incorporate a temperature control mechanism to the fluidised bed combustor.

9.0 Conclusion

Fluidised bed combustion is a reliable method of obtaining clean and renewable energy from agricultural waste like maize cobs.

The fabricated combustor is capable of generating high bed temperatures for steam production. Furthermore, flue gases at over 300 °C have been generated by the system, thereby providing alternative ways for drying and other low thermal applications.

Char produced from maize cobs combustion could be converted to form charcoal briquettes for use in advanced wood stoves, hence, improving the total economic output of the fluidised bed combustor.

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APPENDIX A

Plate 1.: Fluidised bed column

Plate 2.: Perforated distributor grid

Plate.3.: The cyclone

Plate 4 : Assembled Fluidized bed combustor

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