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Pneumatic and Hydraulic Systems in Coal Fluidized Bed Combustor

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Abstract: Problem statement: This study designed the pneumatic and hydraulic systems in coal fluidized bed combustor. These are fluidization of silica sand bed material, Air distributor, centrifugal fan, electric motor power drive and surface heat exchanger. **Approach:** The effects of increased gas velocity on silica sand and the resultant drag force formed the basic equations in fluidization. Air distributor was introduced to achieve pressure drop across the beds. **Results:** The constructed centrifugal fan was driven by selected electric motor based on pressure and temperature changes in the reactor. The dimensions of the heat transfer tube were calculated from fluid flow and energy balance equations. The values obtained were as the follows: Fluidization velocity (1.54 m sec^{-1}), gas velocity through orifice (29.52 m sec^{-1}), the fan electric motor (2 KW, 3 ph at 1500 pm), the steam temperature obtained was 160°C from water ambient temperature of 30°C and tube length 22 m was coiled into levels in the combustor. **Conclusion/Recommendation:** Precise specifications of pneumatic and hydraulic systems will adequately address the environment concern of coal fired power supply as a method to address epileptic power supply in Nigeria.

Key words: Pneumatic, hydraulic, fluidization, distributor, combustor, exchanger, coal

INTRODUCTION

A number of industrial processes such as lime, ceramic tiles, calcinations, cement, Kaolin, aggregates and black powder explosive production utilize combustors. Pneumatic systems create the proper proportion of combustion ingredients that moves the products of combustion to the atmosphere safely at minimum expense and acceptable to environmental protection agencies. The function of hydraulic system is to convert the residual energy in coal into usable state as in coal fired thermal plants and fluidized bed combustors. Proper design of pneumatic and hydraulic systems can influence the efficiency of any combustor.

Heat is transferred to water and steam flowing through the tubes that are in intimate contact with the solid particles. The tubes are in the part of the hot gases[11]. Coal particles in fluidized state have more exposed surface area to combustion and offer good heat transfer properties in a combustor. The changes in bed behaviors were due to airflow velocity increase and the drag force exerted on the particles[4]. Air enters the bed through holes into bed materials between hot fluidized zone and the plate forming the plenum chamber. This can made from mild steel plate, which requires an open area sufficient to cause pressure drop. Air distributor was required to provide uniform distribution for the bed materials used in fluidized bed combustion. The pressure drop about 12% across the bed was required to provide the uniform distribution for the beds in fluidized combustion[7].

The function of the air distributor was to admit the air with sufficient uniformity over the cross section to ensure good fluidization. It supports the weight of static bed without allowing the bed materials to pass into the air plenum chamber[10]. Heat transfer from coal combustion to water in a combustor was mainly through heat exchanger. This is a device, which promotes the transfer of heat from one fluid to the other but in which the two fluids are separated by a wall so that no mixing of the fluid occurs. A one-one counter flow heat exchanger can be designed by forming the stainless steel pipe into coils[8]. The hot fluid flows through the chamber while the cold fluid flows through the tubes. The heat across transfer takes place the wall of the tubes from the hot gases to the cold water. This enables the extraction of the high temperature gases by the surface heat exchanger in the combustion chamber[10]. It is recommended that immersed tubes be used for laboratory and pilot unit in which case the

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temperature of a hot bed can easily be controlled by adjusting the flow rate of the coolant to a limit without condensation. The size of water reservoir necessary depends on the plant as a whole, its method of operation, the size of the water tube, duration in the combustor and the rate of steam production. The steam tank with a gate valve can be used to control the volume of discharge into the water tube. There is need for flow meter to measure the amount of the flow from the tank into the tube. The wet tank was necessary to deliver uniform stream of water through a regulated gate valve. The tank could be constructed from mild steel plate and painted with red oxide to prevent corrosion[11]. Fluidized bed combustor requires air with necessary pressure either by exhausting fan or by blowing (forcing) air through the flame in a closed chamber or the combination of the two[9]. The fan could be varied according to the rate of combustion required. The draught fans are normally independent of atmospheric conditions, which increase the capacity of combustor, enhance the efficiency of heat transfer tubes, cheaper than chimney and permits more perfect combustion. It was necessary to tune the fan and the entire equipment in proper proportion to achieve success.

MATERIALS AND METHODS

Fluidization: The gas velocity was computed at which bed materials become fluidized as follow:

$$V_{mf} = \rho_p \text{ x } d_p^2 \times g/1800 \times \mu \tag{1}$$

According to[4],
Where:
ρ_p = 2600 kg m^{-3}, silica sand density
d_p = 0.001 m (max), diameter of silica sand
g = 9.81 m sec^{-2}, acceleration due to gravity:
μ = 1.85×10^{-5} Kg ms^{-1}, viscosity of air.

$$V_{mf} = \text{min fluidized viscosity} = \frac{2600 \times (0.001)^2 \times 9.81}{1800 \times 1.85 \times 10^{-5}} = 0.77 \text{ m sec}^{-1}$$

According to[3], the min operating velocity, V, through a bed of solids, should be at least 1.3-2 V_{mf} to ensure that the bed materials fluidized. Working within this range: Therefore:

V = lower limit 1.3×V_{mf} = 1.3×0.77 = 1.001 m sec^{-1}

V = Upper limit 2×V_{mf} = 2x 0.77 = 1.54 m sec^{-1}

The fluidization velocity was selected to be V = 1.54 m sec^{-1}, due to immersed heat transfer in-bed tubes, which would impinge on the vertical velocity of the particles.

The terminal velocity was obtained by:

$$V_T = 5.400 \frac{(\rho_p d)^{1/2}}{\rho_a^{1/2}} \tag{2}$$

According to[4],
Where:
ρ_p = particle density = 2600 kgm^{-3}
d = diameter of particle = 0.001 m
ρ_a = air density = 1.18 Kg m^{-3}

$$V_T = 5.4 \frac{(2600 \times 0.001)^{1/2}}{1.18^{1/2}} = 8.01 \text{ m sec}^{-1}$$

According to[1] fan air intake velocity is normally from 5-7 m sec^{-1} before been transformed by pressure changes.

Air distributor: Pressure changes in fluidized bed combustors were obtained according to[10]:

$$\Delta_{pb} = l_{mf}(1 - E)(p_s - p_g)g / g_c \tag{3}$$

Where:
Δp_b = Pressure drop across the bed
l_{mf} = Bed at minimum fluidization = 0.15m (Bed depth)
E_{mf} = Void fraction in a bed at minimum fluidizing condition = 0.44m
p_s = 2600 kg m^{-3}
p_g = Gas density = 1.18 kg m^{-3}
g_c = Conversion factor = 1 kg m N^{-1} sec^2
g = 9.81 m sec^{-2}
E_{mf} = Fraction consisting of solid out of 1
= 0.15(1-0.44)(2600-8) 9.81/1=0.15(0.56)(2598.82) 9.81 = 2141.53 Nm^{-2}[10]

$$\Delta_{pb} = \text{pressure drop across a distributor}, \Delta_{pd} = (0.2 - 0.4)\Delta_{pb} \tag{4}$$

According to[10] 0.4 was selected due to effect of heat exchanger and cyclone associated with the combustor. Δp_d = 0. 4(2141.53) = 856.61N m^{-2}. Reynolds number:

$$R_e = d\, V\, p_g/\mu \tag{5}$$

Where:
μ = viscosity of air = 1.85×10^{-5}

d = bed diameter = 0.32 m
v = 1.54 m sec^{-1}
R_e = 0.32×1.54×1.18/1.85×10^{-5} = 31.433>3000. C_d varies from 0.2-0.6 in relation to Reynolds number according to[10]
C_d = 0.6 was selected. C_d = orifice coefficient, dimensionless.

Orifice Velocity[10]:

$$U = C_d (2(\Delta p_d / p_g)^{½}) \quad (6)$$

Which is the gas velocity through orifice, U = 0.6×(2×(856.61/1.18]$^{1/2}$ = 29.515 m sec^{-1} measured at the approach density and temperature.

This value is satisfactory since it does not exceed the maximum allowable jet velocity of 40 m sec^{-1}.

Number of orifice:

$$N = V X 4/л\, d_r^2\, U \quad (7)$$

= 1.54 x 4/ 3.142 x $(0.004)^2$ x 29.515 = 4152.10/m^2.

Where:
N = No. of orifice per unit area of distributor, m^{-2}
d_r = Orifice diameter = 4mm (selected).

To determine cm^2 per orifice = 1/0.4152 cm^{-2} = 2.40818 cm.

To determine orifice per square cm = $(2.40818)^{½}$ = 1.552 cm.

One orifice in a square plate of 1.552cm.

Number of orifices in the square plate = sum each length of the combustor/square of the orifice = 0.32/0.01552+0.32/0.01552 = 20.61+20.61 = 41.22 holes.

Open area in the distributor at 4mm diameter:

$A_{hole} = \pi d^2/4 = 3.142\ (0.004)^2/4 = 1.256637\times10^{-5}$

Area of the combustor = 0.32×0.32 = 0.1024 m^2
Percentage of open area in the distributor = 1.256637×10^{-5}×41.22×100/0.1024 = 0.52%. This value should vary from 0.5-2% according to[7].

The fraction of open area in the perforated plate V/u =1.54/29.515 = 0.0522 = 5.22%. It should not exceed 10%[10].

About 300 μm screen mesh was also fastened to the air distributor.

The open area selected was 0.52% at 4 mm drilled holes that resulted in 42 holes on the 0.32×0.32 m area of distributor chamber.

Centrifugal fan pressure heads: The air is to be compressed from an initial pressure p_1 to a higher-pressure p_2 to run a fluidized bed combustor by the centrifugal fan as shown in Fig. 3 and the above calculations:

Atmospheric pressure of air intake, p_o = 101 kN m^{-2}
Bed pressure drop Δp_b = 2141.53 w m^{-2}
Distributor pressure drop Δp_d = 856.61 N m^{-2}
But, p_2-p_1 = Δp_b+Δp_d+Δp heat exchanger = 2141.53 +856.61 = 2998.14N m^{-2}
P_3 = p_o+2998.14 at the bed exit = 101+2.998 Kn m^{-2} = 104 kN m^{-2}
P_2 = p_3+Δp_b = 104+2.14153 = 106.141 kN m^{-2}
P_1 = p_2+Δp_d = 106.141+0.85661 = 107 kN m^{-2}

Electric motor power drive calculation: The required power to drive the forced draught fan was obtained as follows:

$$P_1 = hm_1m_2T_I \quad (8)$$

60×36×n_f[9]

Where:

H	=	In mm of water,
10 N m^{-2}	=	1mm of water
1 N m^{-2}	=	1/10mm of water
1 bar	=	101,333 Nm^{-2}
in mm of water	=	1/10 mm of water×101,333 N m^{-2} = 10,133.3 mm of water and 107,000 N m^{-2} = 10,700 mm of water. The listed values were obtained from[11].
m_1	=	Mass of air required = 12.735 kg
m_2	=	Mass of fuel feed rate = 4.861 kg h^{-1} = 0.08102 kg min^{-1}
T_1	=	Ambient temperature = 34°C = 273+34 =307k
T_2	=	Exhaust gas temperature = 273+330 = 603 k
Efficiency of fan	=	80%[9]

$$P_1 = \frac{10,700\times12.735\times0.08102\times307}{60\times36\times0.8} = 1961.41\text{w} = 2\text{kw}$$

Similarly the power required to drive the induced draught fan:

$$P_2 = \frac{10,700\times12.735\times0.08102\times603}{60\times36\times0.8} = 3852.55\text{w} = 4\text{kw}$$

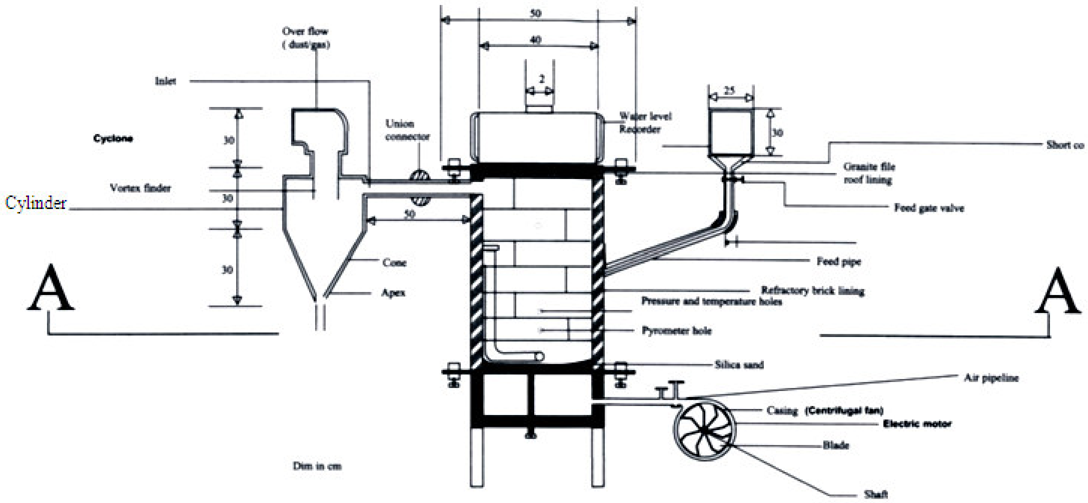

Fig. 1: Front elevation (section A-A) of the fluidized bed combustor

The selected electric motor (2 KW 3 ph at 1500 rpm) is to drive the centrifugal fan as shown in Fig. 1.

Surface heat exchanger: Wet and Steam Tanks Hydraulic System was selected for design. The tank was easily filled up. It allows steady flow of water into the gate valve and flow meter just like a natural pump. It was raised to a height of 200 mm above the level of heat transfer tubes of the combustor:

Volume = L×B×h for the tanks

- $V = 40\times20\times20\ cm^3 = 16{,}000\ cm^3 = 16\ L$

An orifice, circular in shape at the vertical side of the tanks serves as the discharge for the wet tank

- The diameter of the orifice = 20 mm = 0.02 m. The height from the orifice to the heat transfer tubes was 1 m. i.e., height of the combustor:

$$a = \frac{\pi}{4}d^2 = \frac{\pi}{4}\times0.02^2 = 3.14159\times10^{-04}\times m^2$$

- The volumetric flow rate of water: Theoretical discharge through the orifice[8]:

$$Q_{th} = a\sqrt{2gh} \qquad (9)$$

$= 3.14159\times10^{-4}\times\sqrt{2\times9.81\times1} = 3.14159\times10^{-4}\times4.43$
$Q_{th} = 1.39155\times10^{-03}\ m^3\ sec^{-1} = 0.00139155\ m^3\ sec^{-1}$

Actual discharge through the orifice[8]:

$$c_d = 0.625 \quad Q_{ac} = Q_{th}\times c_d \qquad (10)$$

$Q_{ac} = 1.39155\times10^{-03}\times0.625 = 8.6972\times10^{-04} = 0.0008697 m^3\ s^{-1}$

- The velocity of water:_Theoretical velocity of the jet at vena contracta[8]:

$$V_{th} = \sqrt{2\times g\times h} = \sqrt{2\times9.81\times0.2} = 2.0\ m\ sec^{-1} \qquad (11)$$

Actual velocity of the jet at vena contracta ($C_v = 0.98$)
$V_{ac} = V_{th}\times C_v = 0.98\times2.0 = 1.96\ m\ sec^{-1}$.

- Internal diameter of the surface heat exchanger tube

$D = 1.13\sqrt{Q/V}$ (but $Q = 0.0008697\ m^3\ sec^{-1}$, $V = 1.96\ m\ sec^{-1}$)
$D = 1.13\times\sqrt{0.0008697/1.96}$
$D = 1.13\times0.02085 = 0.02356\ m = 20\ mm$ (nearest tenth)

Inside diameter selected was 20 mm with 1mm wall thickness for the surface heat exchanger tubes and were joined to suit the installation. The pipe joints used were socket, elbow, Tee-joint, bushing, stopcock, gate valve, nipple and union connector for the heat exchanger pipelines.

Heat transfer tubes: Feed water and wall temperature: At 30°C for the water, the following characteristic data were obtained from thermodynamic steam table[8]:

$\mu = 8\times10^{-4}$ kg m sec^{-1}
$\rho = 996$ kg m^{-3}
C = 4190 J $kg^{-1}K$
K = 0.643W $m^{-1}K$

Energy balance equation:

$$Q = m_a\, C_a\, (t_{ba}-t_{oi}) = m_w\, C_w\, (t_{wo}-t_o)^{[12]} \quad (12)$$

m_a = Mass flow rate of air = volume flow rate×density air density $\ell = 1.3$ kg m^{-3} at 34°C.

The centrifugal fan blower had the following features: Impeller diameter, D = 250 mm, blade width b = 50 mm and 8 vanes.

The velocity of impeller at inlet with the coupled electric motor, V = π DN/60 13 =3.142×0.250×1500/60 = 19.63 m sec^{-1}[8] Air flow rate:

$$Q_a = \pi D\, b\, V \quad (13)$$

= 3.142×0.250×0.05×19 63 = 0.77 m^3 sec^{-1}[8]
$m_a = 0.77\times1.3 = 1.001$ kg sec^{-1}
t_{ba} = bed temperature = 800°C (between 750-950°C)
t_0 = exit gas temperature = 330°C (not less than 175°C)[12]
C = Specific of heat capacity of air = 1010J kgk^{-1}[12]
m_w= mass flow rate of water = volume flow rate×density
= 0.0008697 m^3 sec^{-1}×1000 kg m^{-3} = 0.8697 kg sec^{-1}
Q = 1.001×1010×(800-330) = 0.8697×4190×(t_{wo}-30)
= 475,174w = 3644.043 t_{wo} -109,321.29w, = 584496w = 3644.043 t_{wo}
t_{wo} = 160.4°C, the steam temperature

$t\Delta_m$ = logarithmic mean

$$\text{temperature difference} = \frac{(t_b - t_{wo}) - (t_o - t_{wi})}{\dfrac{Ln(t_b - t_{wo})}{(t_o - t_{wi})}} \quad (14)$$

$$= \frac{(800-160.4)-(330-30)}{\dfrac{Ln800-160.4}{330-30}} = \frac{339.6}{\ln 0.929} = 448.6K$$

Reynolds number, Re = VDρ/μ
D = 20mm, V = 2.0m/s, ρ = 996kg/m^3, μ = 8x10^{-4}

$$Re = \frac{2.0\times0.02\times966}{8\times10^{-4}} = 4980$$

$$\text{Prandl number}\, P_r = \frac{C\mu}{k} = \frac{4190\times8\times10^{-4}}{0.643} = 5.21 \quad (15)$$

Heat transfer coefficient: For turbulent gas flow, an empirical equation was recommended according to[5]:

$$H = 0.023\frac{k}{d}Re^{0.8}\, Pr^{1/3} \quad (16)$$

The film coefficient on the inside surface: H = 0.023×0.643/0.02 $(4980)^{0.8}\times(5.21)^{1/3}$ = 1156.83W $m^{-2}K$

- The overall heat transfer coefficient based on the outside surface area of the tube U_o, carbon steel material was correlated as in[5.]:

$$1/U_o = 1/H_o + ro/ri\times1/Hi + ro/k\times\ln(ro/ri) + 1/H_{fi} + 1/H_{fo} \quad (17)$$

Where:
H_o = 500 w m^{-2} K for the film coefficient on the outside tube surface of carbon steel.
K_1 = 31 w mK^{-1} for carbon steel tube
H_{fi} = 1000 w m^2k^{-1}, fouling factor on the inside tube surface for carbon steel
H_{fo} = No fouling factor on the outside surface[9]
$1/U_o$ = /500+0.011/0.01(1/1156.8)+0.011/31 ln 0.011/0.01+1/1000 + 1/∞
$1/U_0$ = 0.002+0.000951+0.00003382+0.001+0 = 0.00398482
U_o = 250.95 w m^2K^{-1}

Surface area, number and length of tubes:

- The heat transfer rate was as calculated as follows: The heat release for the tube was Given Q_o = 471,174.7 W:

$$Q = U_o\, A\, \Delta T_{mf} \quad (18)$$

- Surface area of the tubes:

A = Q/ $U_o\times\Delta t_{mf}$ = 475,174.7/251 x 448.6k = 4.22m^2

- The total cross sectional area of tubes in one pass:

$$A_c = \frac{Q_c}{V} = \frac{0.0008697}{2} = 0.00043485\,m^2$$

For the cross sectional area of a single tube to obtain the number and length of tube, r_i = 0.01 m
$A_T = \pi r_i^2 = \pi\times(0.01)^2 = 0.00031415\ m^2$

- The number of tubes in each pass was:

$$N_T = Ac / A_T = \frac{0.00043485}{0.00031415} = 1.38$$

- The surface area of a single tube was $2\pi r_0 l = 2\times\pi\times 0.011\times L = 0.0691$ L

- The tube length, $L = A/2N_T\ (0.0691)$

  $L = 0.27/\ 2N_T(0.0691) = 4.22/2\times1.38\times0.0691 = 22.0$ m
- The number of coils = length of tube/Cross sectional length of combustion chamber. The number of coil = 22.0/0.30 = 70 coils

The tube chosen for this experiment was from stainless steel type 310 but carbon steel preferable austenitic steel such as 304, 316, 321, or 347 grades are also suitable. The pitch between pipe to pipe = 16 mm. The horizontal tubes arrangement was made up of 10 coils of 7 levels in the combustion chamber.

The containment of heat transfer tubes, the reaction of coal and oxidants as well as other design features influence combustion in fluidized bed. The depth to diameter ratio was greater than unity. Rectangular geometry was selected for the combustor. Adequate degree of turbulence occurred as the gas upward velocity was about 29.515 m sec^{-1}. The combustor was constructed from mild steel of 6mm thick. The bed area selected was 0.45×0.45 m with side flanges for airtight coupling.

RESULTS

The Fluidization, Air distributor, Electric motor power drive, Surface heat exchanger, Heat transfer tubes, The film coefficient on the inside surface with Surface area, number and length of tubes were calculated as shown in materials and methods. The analyses of the results of all these calculations were to help in the study. The numerical calculation for fluidization for gas velocity was defined via the formulae suggested by[4], while on distributor was obtained through the formulae given by[10], heat transfer tube was calculated through[8]**,** heat transfer coefficient and the film coefficient on the inside surface were calculated through the recommendation of[5] .

DISCUSSION

Minimum operating velocity: The calculated operating velocity was 1.54 m sec^{-1} while most applications is within the range of 1-3 mL but lower and higher velocities are occasionally justified. Optimum fluidizing velocity can cause savings in capital cost by reducing bed area and power consumption.

Pressure drops: The atmospheric pressure was about 101 KN m^{-2}. The centrifugal fan transformed the atmosphere air to the air box at about 107 KN m^{-2}. This means that the centrifugal fan had 6 KN m^{-2} head. The calculated temperature was 106 KN m^{-2} while the exit pressure to the cyclone was 104 KN m^{-2}. The pressure drops across bed and the distributor were 2.14 KN and 0.857 KN m^{-2} respectively as showing in Fig. 3.

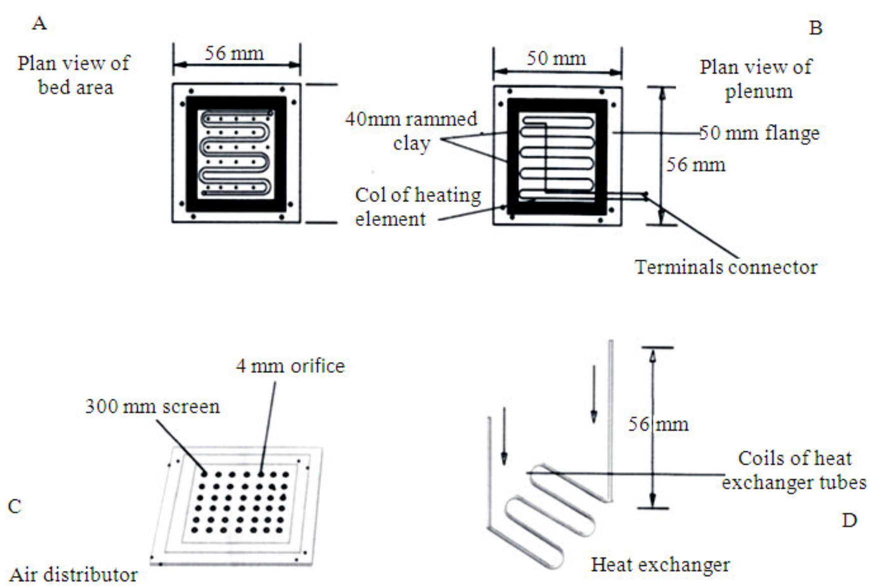

Fig. 2: Components of fluidized bed combustor

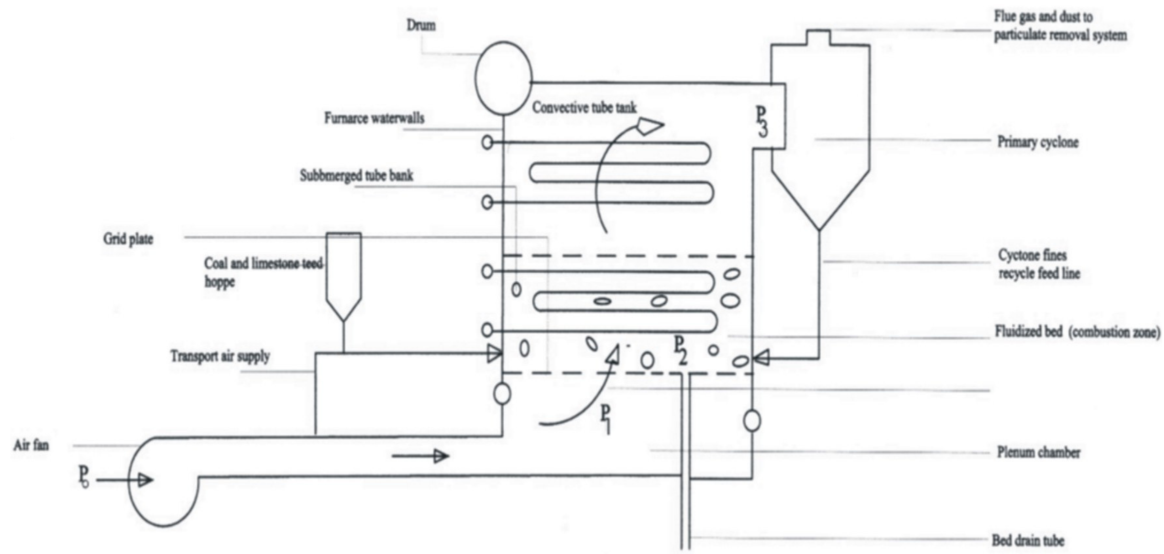

Fig. 3: Schematic of a fluidized-bed-combustion steam generator

Air distributor characteristics: The orifice gas velocity was 29.52 m sec^{-1}, which is below the upper unit of 40 m sec^{-1} for fluidized bed combustion. The percentage of open area in the distributor was 0.52%, which is within the rage of 0.5-2% for atmospheric fluidized bed combustor. The fraction of open areas is also the fraction of the minimum fluidizing velocity to the orifice gas velocity was 5.22% which should not exceed 10% for coal fluidized bed combustors as shown in Fig. 2.

Air and water flow rates: The water and airflow rates obtained were 0.0008697 and 1.008 m^3 sec^{-1} respectively. The electric power calculated to drive the centrifugal fan was 2 kw, 3 ph at 1500 rpm as shown in Fig. 1.

Heat exchange Tube: The energy balance equation of the flow rates resulted in steam temperature of 160.4°C, obtainable from 22 m long tube 20 mm internal diameter, I mm wall thickness, 16 mm pipe pitch, 10 coils and 7 levels in the atmospheric fluidized bed combustor. With improved circulation systems more steam temperature and less of heat loss can be obtained.

CONCLUSION

Coal utilization is gaining attention in recent time as demonstrated by Ashaka Cem Plc on its committed to use coal (lignite) to fire its cement kiln and Royal Ceramics to use Okabba Coal to fire its Kiln. The environmental concern had been eliminated by coal fluidized bed combustion technology. The 'heart and soul' of fluidized-bed combustion are its effective pneumatic and hydraulic systems. The design procedures will provide the basis in combustion control, tune and improve on coal- fired combustors in Nigeria. Coal fired power stations for electricity generation is long over due as oil and gas supply system is not reliable. India, British, U.S.A., China and South Africa obtained more than 50% of their Electricity from coal fired power stations.

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