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ORIGINAL RESEARCH ARTICLE

DETERMINATION OF MAIGANGA LIGNITE COAL COMBUSTION CHARACTERISTICS FOR APPLICATION IN THERMAL POWER PLANT USING STANDARD MATHEMATICAL MODELS

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ABSTRACT
This paper presents determination of Maiganga lignite coal combustion characteristics for application in thermal power plant using standard mathematical models. The problem statement was that Nigeria cement plants uses rotary kiln coal burner despite its associated drawbacks such as sudden explosion and incomplete combustion. Fluidized bed technology has less of the drawbacks associated with rotary kiln coal burner. The integration of Maiganga coal in mathematical models will increase accurate prediction of operating variables useful in design and sizing the components of fluidized bed thermal power plant. The methodology of the study includes utilization of established numerical models based on energy balance and fuel properties for Maiganga lignite combustion. The coal was fired in a pilot atmospheric fluidized bed combustor (FBC). The results obtained include the theoretical air required per kg of Maiganga lignite was 7.4, at an excess air of 10% and maximum mass of air supplied per kg of Maiganga lignite of 8.82. The time for burn out of particle sized 0.4 mm was determined to be 2.64 min, with burning rate of 0.23 kg/min (3.8 g/s). The ignition temperature of 797 K and fuel power of 84 kW for Maiganga coal were determined for the pilot FBC in this study. The Maiganga lignite fuel, air and sorbent flow rates through the fluidized bed combustor were predicted to be 14.2 kg/hr (0.23 kg/min), 202.4 kg/hr and 1.26 kg/hr respectively. The combustion performance evaluation of the fluidized bed combustor had specific firing rate for the lignite at graded particle size of between 0.2-1.12 mm at bed temperature of 1173 K was 2.8 g/m^{2}s, air-fuel ratio of 23 and equivalence ratio of 0.45. The above results are similar to coal burnout time of 3 minutes and equivalence ratio of 0.40 in an atmospheric fluidized bed combustor in the literature. Hence, above parameters can be used to design and model a safe ignition and good combustion characteristics in other lignite fired power plants similar to that of Maiganga lignite coal.

1.0 Introduction

Maiganga coal is mined and processed for combustion in rotary kiln coal burner for cement production by Ashaka cement plant. The combustion of Maiganga coal takes place in the presence of high temperature, turbulence and continuous air flow that results in rapid oxidation, ignition and hot flame in an enclosure like rotary kiln burner and fluidized bed combustor. Modular coal-fired thermal power plant developments have increased in Nigeria with proposed Okobo coal-fired power plant at capacity of 1200 MW and others. Exploitation of coal by surface working method from Maiganga hills, near Kumo in Gombe, commenced in October, 2007. The combusting of Nigerian coals in rotary kiln coal burner is about a decade in Nigeria and the technology have spread from Ashaka cement plant to cement plants at Obajana, Ibese, and Sokoto. The rotary kiln coal burner has drawbacks such as sudden and frequent coal explosion as well as incomplete combustion. Fluidized bed coal combustion technology has less of the drawbacks associated with rotary kiln coal burners.

Mathematical models in the form of equations, graphs or tables can be used to represent and predict phenomena as in fluidization and combustion. Mathematical models contribute to better understanding of the processes in thermal power plants (Alobaid, et al., 2016). The fuel properties in the modelling are to advance an established fact that moisture, volatile matter, oxygen, hydrogen contents among other factors contributes to combustion as reported by Ngampradit et al. (2004). There are several combustion models that had addressed various parts of fluidized bed combustion available in literature. An example was computational fluid dynamics (CFD) combustion model for biomass for different particle sizes in a fluidized bed as reported by Li et al. (2015a). The integration of Maiganga coal in fluidized bed combustion models have received little attention. Mathematical models applications have increased accurate prediction of operating variables such as air flow rate, fuel flow rate among others for complex fluidization processes in combustor. These operating variables are in turn useful in design and sizing the components of the fluidized bed thermal power plant.

Lee (1997) investigated heat transfer and combustion in advanced swirling fluidized bed combustor. He formulated the basic governing equations based on continuity, energy equations, chemical reaction and radiation heat transfer. Ngampradit et al. (2004) simulated a circulating fluidized bed combustor with shrinking core and emission. Their work was to predict proper amount of fuel blend and to reduce emission from coal combustion. The researchers attained improvement in the solid fuel size change during the combustion. The researchers also added emission models to predict the formation of NO, N_2O and SO_2, which can be used for environmental prediction consideration. Similarly, Mikulcic et al. (2014) reported numerical study of co-firing pulverized coal and biomass inside a cement calciner. The results show that when combusting biomass in an existing pulverized fuel burner, special attention need to be given to complex oxidation of char particles to avoid unpredicted emission of hot fly ash. Their numerical models improve better understanding of particle kinetics in the operation of the calciner in reduction of pollutant formation. Marra et al. (2014) worked on fluidized bed combustor coupled with a sterling engine for co-generation purposes, which consisted of heat transfer, energy balance in fluidized bed and the relationship between power, efficiency and torque at assigned geometrical parameters and physical properties of sterling engine. More efficient heat transfer due to multiphase fluidized medium was attainable than heat transfer tubes immersed in flue gases during their study. The abrasion action of solid particles also reduces fouling of the heat exchanger surfaces that are associated with coal and biomass combustion. However, the contribution of diameter and length of heater tubes on performance prediction without loss of efficiency and power needs further investigation. Johnson (2007)

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worked on biomass-fired fluidized bed combustion for clean energy production with advantage to reduce exhausted SO_2, CO_2 and particulates from the flue gas in comparable to fossil fuel combustion under similar circumstances. The researcher essentially reviews the trend of development of fluidized bed technology and made an outlook into the future without discussing the challenges associated with combustion of solid and gas in each of the mentioned fluidized bed technologies. Thapa et al. (2016), centered their work on physics of fluidization and chemistry of fuel combustion. Their modeling and simulation focused on various flow regimes enriched with olivine, coal char and their mixture in air fed into fluidized bed combustion reactor. Their short coming was the proportion of total gas feed rate into bottom and primary were not included in the modeling process. Sarroza et al. (2017), investigated the ignition characteristics of pulverized coal, biomass and co-firing by use of a visual drop tube furnace and a high-speed imaging technique camera. The results indicated effect of volatile matter content in coal and alkali metal present in biomass on the distance to ignition as captured by the camera. However, the distance to ignition point measured by the camera is different to ignition temperature except a correlation was employed.

The process of coal combustion involves heating up, drying, devolatization and char oxidation as variously reported by researchers such as Basu (2015) and Li et al. (2015b). However, there are difficulties connected with combustion of coal in thermal power plants. Some of the key challenges include sudden fire explosion, which are threats to safety in addition to economic losses. The main causes of undesirable explosion were attributed to contact with hot surfaces by leakages of coal particles and oil from startup burner, main burner and flue gas cleaning devices like electrostatic precipitators. In addition, sudden explosion can occur in thermal power plants due to external factors such as smoking, open flame, welding, among other factors but can be handled with good working habits. The external factors in explosion have several protection and prevention techniques reported by Chunmiao et al. (2011). The challenges are inherent factors in fuel, that aid sudden explosion as reported by Eckhoff (2003). It is desirable to minimize this challenge to ensure safe combustion and encourage use of coal, instead of idle and unexploited coal deposit asset, in several places of the world.

Researches on Maiganga coal had mainly be on proximate, ultimate, petrographic, ash, thermographic and radiological analyses as well as calorific value determination, while combusting the coal in furnaces and burners are scanty in literature. In this work, Maiganga coal was analyzed for prediction of combustion characteristics for application in thermal power plants using standard mathematical models. Maiganga coal has proven reserve of about 760 million metric tons and is found in Maiganga hills, near Kumo, along Gombe-Yola Road, in Akko Local Government Area of Gombe State, Northeastern part of Nigeria as reported by Idriss et al. (2018). The deposit lies within longitude 11°20’E and latitude 10°20'N.

The aim of this research is to study the Maiganga coal combustion characteristics for application in thermal power plants using standard mathematical models. The objectives are to determine the Maiganga lignite fuel properties and its combustion stoichiometry; calculate the Maiganga lignite burning rate and its fuel power; evaluate the fuel, air and sorbent flow rates through the combustor as well as to conduct performance evaluation of the combustor and validation of the models.

2. Methodology

2.1 Determination of Maiganga Lignite Fuel Properties and Combustion Stoichiometry

The Maiganga lignite samples were collected from Maiganga coal mine owned by Ashaka Cement Plc, and was prepared according to ASTM standard of D2234 (ASTM, 1990) for the particle size analysis which was carried out at National Metallurgical Development Centre, Jos. The proximate and ultimate analyses of the Maiganga lignite coal were performed according to ASTM standards described in codes D3173, D4239, D3174, D5142 and D5373 (ASTM, 1990). The proximate and ultimate analyses as well as the calorific value had been carried out by several researchers such as Idriss et al. (2018), Tikpangi (2016) and Ryemshak and Jauro (2013), which were adopted for this work. The properties of gypsum and particle size distribution were determined in this work at National Metallurgical Development Centre, Jos. Determination of particle size distribution of crushed and ground coal and gypsum as well as coal combustion in a pilot fluidized bed combustor were carried out. Mathematical models for Maiganga lignite combustion in fluidized bed were selected from established models on energy and mass balances from literature. The models were used to estimate performance of the Maiganga lignite fired in a combustor. The theoretical air required per kg of fuel, excess air required and actual mass of air were obtained by substitution of proximate and ultimate analysis of Maiganga lignite in the stoichiometry equations (Balleney, 2007; UNEP, 2006). The theoretical air required per kg of fuel (TA) was determined using equation (1) as given by Balleney (2007):

$$T_A = \frac{100}{23}\left(\frac{8C}{3} + 8(H_2 - \frac{O_2}{8}) + S\right) \qquad (1)$$

where:

C is carbon content in the ultimate analysis of Maiganga lignite

H_2 is hydrogen content in the ultimate analysis of Maiganga lignite

O_2 is oxygen content in the ultimate analysis of Maiganga lignite

S is sulphur content in the ultimate analysis of Maiganga lignite

The amount of excess air required (EA) calculated using equation (2) as given by UNEP (2006):

$$E_A = \frac{O_2 \times 100}{21 - O_2} \qquad (2)$$

where:

O2 is oxygen content in the ultimate analysis of Maiganga lignite

The actual mass of air supplied per kg of fuel ($\Im$) was calculated using equation (3) as given by UNEP (2006):

$$\Im = (1 + \frac{E_A}{100}) \times T_A \qquad (3)$$

where:

EA is excess air required for the Maiganga lignite combustion (%)

TA is the theoretical air requirement per kg of Maiganga lignite fuel.

2.2 Maiganga Lignite Fuel Burning Rate and Fuel Power

2.2.1 Burning rate constant and time for burn out of lignite

The burning rate constant (K_b) was obtained using equation (4) as given by Turns (2000):

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$$K_b = \frac{8\rho_2 D \ln(1+B)}{\rho_c} \qquad (4)$$

where:

ρ_2 is approximately gas-particle density (kg/m^3)

D is diffusion coefficient for lignite coals (m^2/s)

B is transfer number in combustion of lignite coal for O_2 and CO_2 diffusion = constant

ρ_c is bulk density of Maiganga lignite coal at graded size (kg/m^3)

The lignite particle burn-out time was determined using equation (5) as given by Turns (2000):

$$t_c = \frac{d_c^2}{k_b} \qquad (5)$$

where:

d_c is initial lignite particle size (mm)

K_b is burning rate constant (m^2/s)

2.2.2 Lignite burning rate (F_f)

The burning rate (kg/hr) was calculated using equation (6) as follows (Turns, 2000):

$$F_f = 4\pi r_c \rho_2 D \ln(1+B) \qquad (6)$$

where:

r_c is maximum lignite coal particle radius (mm)

2.2.3 Energy balance in lignite coal combustion

The chemical heat of Maiganga lignite coal in combustion was obtained as the product of burning rate and the lignite lower calorific value (LCV) as expressed in equation (7). Thus:

$$Q = F_f LCV \qquad (7)$$

where:

Ff is lignite coal burning rate or lignite flow rate (kg/hr) (Ozigis and Arudi, 2013)

LCV is lignite coal calorific value (kJ/kg)

Q is energy capacity (KJ/hr) or (W)

Therefore, bed temperature in the combustor was determined using equation (8) as follows:

$$\frac{dT_b}{dt} = \frac{F_f LCV}{m_f C_f} \qquad (8)$$

where:

m_f is mass of the lignite coal in combustor (kg)

C_f is specific heat capacity of the lignite coal (kJ/kgK)

2.3 Maiganga Lignite Fuel, Air and Sorbent Flow rates in the Combustor

2.3.1 The quantity of air supplied into fluidized bed combustor

The quantity of dry air at atmospheric pressure supplied by centrifugal fan for combustion was determined using equation (9) as follows (Highley and Kaye, 1983; Ozigis, et al. 2015):

$$F_a = (F_f + T_A)(1 + E_A) \quad (9)$$

where:

F_a is the air flow rate from the centrifugal fan (kg/hr)

F_f is fuel flow rate (kg/hr)

T_A is theoretical air (kg of air/kg of fuel)

E_A is excess air (%)

The volumetric flow rate (Q_a) of air was found using equation (10) as given below:

$$Q_a = {F_a}/{\rho} \quad (10)$$

where:

ρ is density of air (kg/m^3)

Q_a is volumetric flow rate (m^3/s)

2.3.2 Particle surface temperature

The surface temperature attained by lignite coal particle was determined from coal particles rate of heat transfer (Q) to bed materials using equation (11) as given by Broughton and Howard (1983):

$$Q = h_c A_c (T_f - T_b) \quad (11)$$

where:

A_c is surface area of the particles (m^2)

T_f is particle surface temperature (K)

T_b is bed temperature (K)

h_c is heat transfer coefficient of coal particle (W/m^{2}K) as using equation (12) obtained from Broughton and Howard (1983):

$$h_c = \frac{2k}{d_c} + \frac{0.016}{\sqrt{d_p}} \quad (12)$$

where:

d_p is sorbent gypsum particle size (mm)

K is thermal conductivity of the combustion gas (W/m.K)

Therefore, the surface temperature of lignite in combustor was determined using equation (13) as follows:

$$\frac{dT_f}{dt} = \frac{h_c A_c (T_f - T_b)}{m_f C_f} \quad (13)$$

where:

m_f is mass of the lignite coal in combustor (kg)

C_f is specific heat capacity of the lignite coal (kJ/kgK)

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2.3.3 Sulphur Removal by Sorbent in Maiganga Lignite Coal Combustion

The mole flow rate of sulphur (F_{sm}) in gypsum was calculated using equation (14) given by Nag (2009):

$$F_{sm} = \frac{F_f \times S}{M_{mws}} \quad (14)$$

where:

F_f is burning rate of Maiganga lignite coal or flow rate (kg/hr)

S is percentage of sulphur content in Maiganga lignite (%).

M_{mws} is molecular mass of sulphur (kg/kmol) (obtained from periodic table).

However, the flow rate of calcium at calcium to sulphur ratio of 3:1 (molar basis), is to limit emissions of SO_2 adequately and was calculated using equation (15) as given by Nag (2009):

$$F_c = F_{sm} \times molar\ ratio \quad (15)$$

where:

F_c is flow rate of calcium (Kmol/hr)

Mass flow rate of $CaSO_4$ (F_{cs}) was determined using equation (16) as given by Nag (2009):

$$F_{cs} = M_{mwg} \times F_c \quad (16)$$

where:

M_{mwg} is molecular mass of $CaSO_4$ (kg/kmol)

Fcs is mass flow rate (kg/hr)

The percentage of $CaSO_4$ in gypsum was determined using equation (17) as follows:

$$\%CaSO_4 = \frac{M_{mwg}}{M_{mw\,gypsum}} \times 100 \quad (17)$$

where:

M_{mw} gypsum is the molecular mass of gypsum ($CaSO_4.2H_2O$) (kg/kmol)

Therefore, mass flow rate of gypsum (F_g) was calculated using equation (18) as follows:

$$F_g = {F_{cs}}/{\%CaSO_4} \quad (18)$$

where:

F_g is sorbent flow rate (kg/hr)

Comparing fuel flow rate to sorbent flow rate, the sorbent gypsum constitutes

$$\frac{F_g}{F_f} \times 100$$

.

Heat lost for sulphur removal by sorbent gypsum reaction during combustion was calculated using equation (19) as given by Kataja and Majanne (2007):

$$\frac{m_g C_{pg} dT_g}{dt} = xh_c \tau_g (T_f - T_g) + F_g C_{pg} (T_b - T_g) \quad (19)$$

where:

x is total exposed surface area of ejected sorbent gypsum (m^2)

τ_g is residence time of sorbent gypsum in the combustor (s)

C_{pg} is gypsum specific heat capacity (kJ/kgK)

T_g is gypsum temperature in bed (K)

m_g is mass of sorbent gypsum fed into the combustor (kg)

Therefore, temperature of sorbent gypsum in the combustor was calculated using equation (20) as follows:

$$\frac{dT_g}{dt} = \frac{xh_c\tau_g(T_f - T_g) + F_g C_{pg}(T_{bed} - T_g)}{m_g C_{pg}} \quad (20)$$

2.4 The Combustion Performance Evaluation of the Fluidized Bed Combustor

The performance parameters include specific firing rate, air-fuel ration and equivalence ratio.

Specific Firing Rate

The specific firing rate (SFR) was estimated using equation (21) as given by Broughton and Howard (1983):

$$S_{FR} = \frac{m_f}{At} = m_c D\Delta P_b \quad (21)$$

where:

m_f is mass of fuel burnt (kg)

A is the area of air distributor based on total area of orifice diameter (m2)

t is time for combustion (s)

m_c is molecular mass of Maiganga lignite coal

ΔP_b is the bed pressure

D is reaction rate coefficient for coal at 1173 K

2.4.2 Determination of air fuel ratio

Air fuel ratio (AF) was determined using equation (22) as given by Crawford (1980):

$$AF = \frac{28.97 \times n_a}{m_c \times n_m} \quad (22)$$

where:

n_a is number of moles of oxygen plus number of moles of nitrogen.

m_c is molecular weight of Maiganga lignite coal = 12

n_m is number of moles of Maiganga lignite coal = 1.

2.4.3 Equivalence ratio of fuel combustion in the combustor

Equivalence ratio was defined and calculated using equation (23) as given by Ramirez, et al. (2007):

$$E = \frac{R_L}{AF} \quad (23)$$

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where:

R_L is air-fuel ratio minimum and specific to the combustor

AF is air fuel ratio

R_L is air-fuel ratio minimum and specific to the combustor was calculated using equation (24) as given by Ramirez, et al. (2007):

$$R_L = \frac{F_a}{1.292 \times F_f} \quad (24)$$

where:

F_a is air-fuel ratio in the combustor

F_f is air fuel ratio

The combustor's equivalence ratio was determined in terms of flow rates and air-fuel ratio using equation (25) as follows:

$$E = \frac{F_a}{1.292 \times F_f \times AF} \quad (25)$$

where:

AF is air fuel ratio

F_a is the air flow rate from the centrifugal fan (kg/hr)

F_f is fuel flow rate (kg/hr)

2.5 Computing Procedure

The data from proximate and ultimate analysis, pilot fluidized bed combustor (FBC) were used to validate the models, which were computed as design data shown in Table 2. The developed ordinary differential equations were numerically integrated over time, bearing in mind the assigned initial values of bed, sorbent gypsum and particle surface temperatures. M-file and programme base on combustion parameters were developed for ODE 45 and were run on MATLAB. The programme was used to determine temperatures at various parts of the combustor as well as the burning rate, specific firing rate and equivalence ratio of coal combustion. The results were presented in the form of Tables and Figures.

3. Results and Discussion

3.1 Maiganga Lignite Fuel Properties and Combustion Stoichiometry

The proximate and ultimate analysis of Maiganga lignite and Tongo gypsum are as shown in Table 1. A high volatile matter indicates long flame and more smoke from the fuel when fired. Volatiles ignite first and sustain the process of combustion. Maiganga coal with 30.5% volatiles and average calorific value of 22 MJ/kg, implies it is a lignite but close to sub bituminous coal as with description in ASTM (Oka, 2004). Tongo gypsum indicates that it could react with coal during combustion because of its high calcium content (36.01%); hence, useful as sorbent material. Thus, sulphur presence in solid fuel can be removed with addition of gypsum. Calcium is among materials that can cause reduction of SO_2 emission in co-firing of coal in combustor as reported by Rokni, et al. (2017). The Maiganga coal proximate and ultimate analysis as shown in Table 1, were adopted for the modelling to predict the combustion characteristics. The proximate analysis for Maiganga lignite in this work are within the mean values of moisture (11.03%), volatile (36.10%), carbon (45.96%) and ash (6.91%), respectively, as reported by Tikpangi (2016). The oxygen content (11.38%) and calorific value (22 MJ/kg (4982 Cal/g)) reported by Ryemshak and Jauro (2013), were similar to the results of oxygen content and calorific values reported in this work. Maiganga lignite fuel properties differences from one location to the other locations, according to Ikwuagwu and Uzoegbu (2017), which were due to environmental and temperature effects on lignite at different depths and locations within an area, similarly, reported by researchers on this Maiganga lignite deposit. However, the percentages of moisture and ash of Maiganga coal in this work differ to results reported by Ikwuagwu and Uzoegbu (2017), due to variation in air-dried or oven dried of the feedstock. The particle size distribution for the Maiganga lignite ranges from 0.2 mm to 1.12 mm was an effective specific surface area for an efficient combustion in the pilot fluidized bed combustor, after removal of foreign matters by using appropriate sieves. However, particle size can be less than 75 μm for coal burner in cement rotary kiln as reported by Song et al. (2018). Particle size distribution range for burners helps to minimize oversize and under size that can cause large particle breakages and coal hang-up. Coal hang-up occurs due to coal moisture in thermal power plant, which can cause sudden explosion. During coal combustion, hot flashes and fly ashes from finer particles can ignite other material that can lead to sudden explosion in combustors such as in rotary kiln burner for cement production.

Table 1: Proximate and Ultimate Analysis of Maiganga Lignite and Gypsum

S/N	% Composition	Maiganga Lignite Coal*	Tongo Gypsum
1	Moisture	13.7	20.93
2	Volatile Matter	30.5	
3	Ash	10	
4	S	0.56	18.62
5	C	56	
6	N_2	0.91	
7	H_2	3.86	2.34
8	O_2	10.05	55.76
9	CaO		32.57
10	SO_3		46.5
11	Ca		23.28
12	Calorific Value (MJ/kg)	21-23	
13	%$CaSO_4$		79

*Adopted from Idriss, et al. (2018), Tikpangi (2016) and Ryemshak and Jauro (2013)

Combustion stoichiometry is aimed to determine exactly the quantity of air needed to oxidize fuel that results in stable flame and safe products. The presences of CO_2, SO_2, CO, among others, will require monitoring to prevent concentration beyond approved limit and to take decision on type of explosion venting devices to minimize fire explosion. In addition, prevention of CO in flue gas cleaning devices like electrostatic precipitator will minimize fire explosion. Table 2 has

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stoichiometric quantity of air per kg of Maiganga coal, which took into account the moisture content. Above stoichiometric quantity of air per kg of 7.423 kg, will result in warm flue gases while below will result in fuel rich mixture as reported in Turns (2000). Complete combustion of a rich mixture that results in fuel built up at burner can lead to sudden explosion; hence avoidance of fuel rich in thermal plant is desirable. The excess air in this work varies between 10-20% but with preference for 10% depending on particle size. According to Gupta (2007), coal requires about 50% excess air to completely burn, depending on fuel particle sizes, which differ from excess air in this work. Sufficient excess air has tremendous influence in minimization of sudden explosion in fuel combustion. Conversely, when minimum amount of air was supplied, part of the fuel will not burn due to lack of intimate contact between air and coal.

Table 2: Computed Design Data for the Combustion

S/N	Description	Unit value
1	Theoretical air required per kg of fuel	7.4
2	Excess air (%)	10
3	Maximum mass of air supplied per kg of fuel	8.82
4	Burning rate constant (m^2/s)	6.32×10^{-8}
5	Time for burnt out at 0.4-10mm particle size (min)	2.64
6	Burning (Fuel flow) rate (kg/min)	0.23
7	Power in fuel (kW)	84
8	Air flow rate (kg/hr)	202.4
9	Sorbent (gypsum) flow rate (kg/hr)	1.26
10	Specific firing rate (SFR) (kg/m^2.min)	0.168
11	Air-fuel ratio	23
12	Equivalence ratio of the Maiganga lignite fuel combustion	0.45

3.2 Maiganga Lignite Burning Rate and Fuel Power

Coal particle burning rate was determined by computation of burning rate constant and time for burnt out with values as shown in Table 2. The time for burn out of particle sized 0.4 mm was determined to be 1.74 minutes, with burning rate of 0.23 kg/min (3.8 g/s). Burn out time depends on particle size, bed temperature and coal characteristics as reported by Broughton and Howard (1983). Similarly, burning rate in fluidized bed was reported in one instance as 6.0 g/s for particle sized 3.0-10 mm at bed temperature of 985-1110 K by Oka (2004) as against 3.8 g/s (0.23 kg/min) in this work. The coal burning time can last up to 33 minutes and devolalization takes up to 10-100 seconds, depending on the type of coal and particle size as reported by Oka (2004). The optimum burning rate at particle size of 0.4 mm was 0.23 kg/min (0.0038 kg/s), similar to burning rate of palm kernel-sawdust briquettes determined to be 0.002-0.006 kg/s for boiling water test as reported by Kuti (2009). Therefore, burning rate depends on intensity of O2 diffusion towards the coal particle surface, rate of chemical reaction and increases with char particle size. The ignition temperature of 797 K for Maiganga coal was determined in this pilot fluidized bed combustor as previously reported by Ozigis, et al. (2013). Ignition temperature and burning rate are useful for safety issues due to explosiveness of coal dust when fired in a combustor.

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3.3 Maiganga Lignite Fuel, Air and Sorbent Flow rates through the Combustor

The fuel, air and sorbent flow rates were 0.23 kg/min, 202 kg/hr and 1.26 kg/hr respectively, as shown in Table 2. The fuel and airflow rates promote turbulence, sustenance of combustion and flame front and collectively affect particle surface temperature. Burning rate is equated to fuel flow rate in coal-fired fluidized bed combustor, because no fuel is allowed to hang and build up in combustor to minimize explosion as reported by Broughton and Howard (1983). Fuel build up and burner flame stabilization were managed with controls to minimize sudden explosion, often with smoke and heat detectors as well as elimination of leaks from oil guns, oil burner light up operations and finer particles from fuel ducts as reported in Broughton and Howard (1983). The profiles for particle surface, bed and sorbent temperatures against Maiganga lignite burning time in a pilot FBC are as shown in Figure 1. Some of the predictable factors to minimize frequency of fire explosion in coal burner include particle size, fuel moisture level, sorbent, bed and particle surface temperatures. In addition, first in and first out policy for coal storage and usage will minimize spontaneous combustion as well as avoidance of wet and dry coal particles that can cause clogging in fuel feed line and in screw feeder. The particle surface temperature of 1800K obtained for Maiganga lignite in this work was close to flame temperature when compared to particle surface temperature of bituminous coal of 2445 K reported by Sarroza, et al. (2017). The main reason for sluggish increase of sorbent gypsum temperature that was predicted by the models was due to its high calcium content in the Tongo gypsum. The practice of blending coal with gypsum to remove sulphur in coal is not wide spread in thermal power plants in developing countries. The mass flow rate of gypsum at 1.26 kg/hr will remove sulphur in coal, and will also minimize sudden and undesirable explosion in combustor. In this work, Tongo gypsum had flow rate at 9% in Maiganga coal with sulphur content of 0.56%, similar to a coal-fired fluidized bed boiler that had flow rate of limestone at 40% in a coal with sulphur content of 3.6% as reported by Nag (2009).

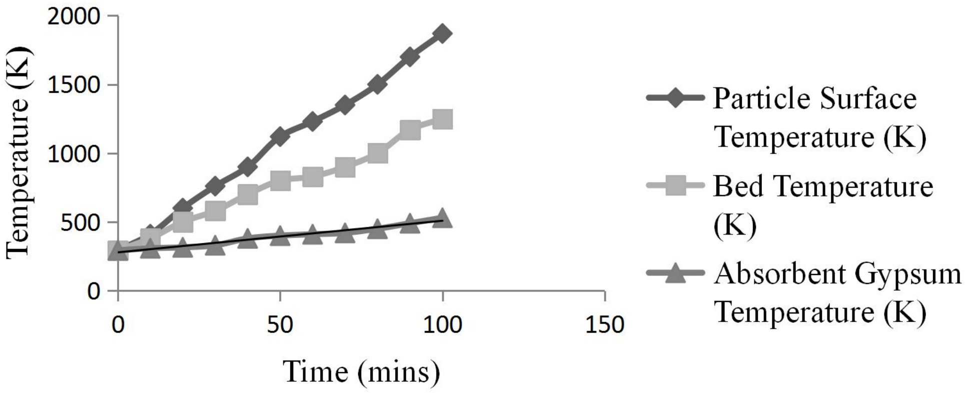

Figure 1: Maiganga Lignite Particle Surface, Bed and Gypsum Temperature against Time

3.4 Combustion Performance Evaluation of the Fluidized Bed Combustor

The Maiganga lignite particle sizes relationship with burning rate, specific firing rate (SFR) and equivalence ratio are as shown in Figure 2. The lower the SFR, the more economical the fuel burnt. Hence, Maiganga lignite is suited for combustion in particle sizes more than 0.4 mm to achieve high equivalence ratio that approaches 0.45, whereas less than particle sizes of 0.4 mm, the equivalence ratio decreases from 0.15 to 0.05. It has been recognized that the performance

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of combustor depends mainly on equivalence ratio range used. The lower limit of equivalence ratio range was determined by the minimal amount of air required to oxidize fuel and generate enough heat to maintain combustion process. Low values of equivalence ratio would reduce bed temperature and the energy liberation necessary to maintain the combustion processes. On the other hand, high equivalence ratio would cause increases in bed temperature due to increase in oxygen diffusion as reported by Ramirez et al. (2007).

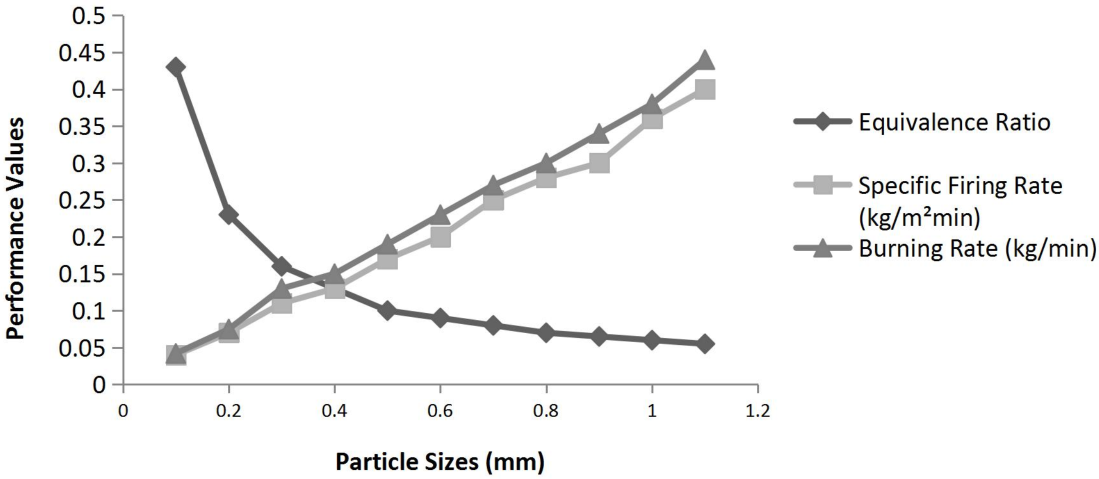

Figure 2: Effects of Maiganga Lignite Particle Sizes on Performance of the Combustor

3.5 Validation of Mathematical Models

Presented in Table 3 is the comparison of model results with other results in literature. The modelled fluidized bed combustor had fuel and airflow rates of 14.2 kg/hr and 202.4 kg/hr respectively, obtained in this work at a bed temperature of 1173 K. The burning (flow) rate of 14.2 kg/hr and airflow rate of 202.4 kg/hr can be employed in design of screw feeder for metering of ground coal and centrifugal fan for supply of air to the combustor, respectively. The FBC had fuel to airflow rates ratio of 0.071, due to excess air of 10%. The ratio of fuel to airflow rates in standard fluidized bed combustor is within 0.15 as reported by Alobaid, et al. (2016). Tri-Tordai, et al. (2010), reported co-combustion of coal and biomass with power output of 45-90 kW in that work. Optimizing airflow and fuel flow can result in uniform and efficient combustion as reported by Wiatrus-Motyka (2016). Also, another modelled coal combustion resulted in a particle burn out time of 3 minutes at specific firing rate of 3.83 g/m^{2}s at a bed temperature of 1173 K as reported by Broughton and Howard (1983). On the other hand, Maiganga lignite coal had burn out time of 2.64 minutes with corresponding specific firing rate (SFR) of 2.8g/m^{2}s (0.168 kg/m^{2}min) at bed temperature of 1193 K obtained in this work. SFR is a measure of intensity of combustor operation, control of flame lift and as an estimate for comparing various coal-fired burners. SFR will guide sizing of air distributor, orifice diameter and estimation of coal flow rate into combustor for efficient firing devoid of fuel rich combustion. Furthermore, Maiganga lignite coal combustion at equivalence ratio of 0.45 obtained in this work is similar to an equivalence ratio of 0.40 for rice-husk-fired fluidized bed gasifier reactor as reported by Ramirez et al. (2007). The bed temperature obtained for Maiganga coal during burning ranges from 1103 to 1223 K. This is similar to bed temperature of 1273 K for coal-fired furnace reported by Li, et al. (2010). All the Maiganga coal models results were compared with other results in literature with good agreement. Therefore, the selected mathematical models have been validated and can be used appropriately in limiting sudden explosion and raise more interest in fluidized bed burners for cement production and for modular coal-fired thermal power plants.

Table 3: Comparison of Model Results with Literatures

S/N	Parameters	Model Results for Maiganga Lignite	Results Obtained From Literature	
1	Maiganga fuel flow rate (kg/hr)	14.20	40-80	Tri-Tordai et al. (2010)
2	Air flow rate (kg/hr)	202.4	297	Tri-Tordai et al. (2010)
3	Particle burn out time (min)	2.64	3.0	Broughton and Howard, (1983).
4	Bed Temperature (K)	1103-1223	1275	Li et al. (2010)
5	Equivalence ratio	0.45	0.4	Ramirez et al. (2007)
6	Thermal energy output (kW)	84	45-90	Tri-Tordai et al. (2010)

4. Conclusion

This work presents determination of Maiganga lignite coal combustion characteristics for application in thermal power plant using standard mathematical models. The conclusions drawn were that particle size distribution can minimize sudden explosion from fly ash particles and moisture in coal fired in combustor needs to be minimized to avoid clogging that can lead to explosion while sorbent gypsum will minimize bed temperature. The ignition temperature of Maiganga lignite coal was determined to be 797 K. The models were used to determined Maiganga lignite fuel to have air-fuel ratio of 23 and equivalence ratio of 0.45. The airflow rate of 202.4 kg/hr will form the basis for design of centrifugal fan for forced air supply into the combustor. The Maiganga lignite-burning rate of 14.2 kg/hr with burn out time of 2.64 minutes for particle size graded at 0.4 mm was determined. The burning rate of 14.2 kg/hr will aid the design of screw feeder for supply and metering of ground Maiganga lignite fuel into the combustor. The specific firing rate for Maiganga lignite at 0.4 mm particle size and at 1173 K bed temperature was 2.8 g/m^{2}s. The specific firing rate of 2.8 g/m^{2}s, will guide the design of surface area of air distributor, orifice diameter and for estimation of rate of coal into the combustor for efficient firing devoid of fuel rich combustion.

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