ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETE September 2022. Vol. 18(3):527-540
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2644, Electronic ISSN: 2545-5818
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

MODELLING COMBUSTION CHARACTERISTICS OF SOME SELECTED NIGERIAN COAL SAMPLES

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ARTICLE INFORMATION

Submitted 5 February., 2022
Revised 26 April, 2022
Accepted 30 April, 2022

Keywords:
Thermodynamics analysis
Aspen Plus
Nigerian coal samples
pulverised coal
coal combustion

ABSTRACT

Coal is one of the most abundant fossil fuel which could be utilized for electricity production using different techniques. The pulverization technique is considered in this study which involves coal combustion to release heat which can be utilised to generate steam. Grinding and drying are prior combustion processes that increases rate of reaction during combustion. This study determines the thermodynamics characteristics of coal combustion using the pulverization technique for Five Nigerian coal samples (Odagbo, Owupka, Ezimo, Amansiodo and Inyi Coal). A process based model was developed using ASPEN PLUS for a coal power plant. The mass balance and energy balance equations for the plant components was used. Emission from coal combustion was determined at different equivalence ratios of 1, 0.7, 0.5, 0.4 and 0.3 respectively. It was observed that excess air supplied reduces emissions and there is a trade-off of combustion temperature. Also, the amount of ash released is independent of the equivalence ratio. From results obtained, at stoichiometry, Owupka coal sample has the highest combustion temperature of 2005°C and the least ash production of 1.3kg/s while Inyi coal has the least combustion temperature of 1779°C and the highest ash production of 18.8kg/s. Therefore, Owupka coal is recommended for use as it has the highest efficiency when used in combustion. Also, to improve the efficiency of Inyi coal sample, it is recommended to be mixed with high efficiency coals like Owupka.

1.0 Introduction

For decades, coal has been fundamentally utilized for power generation, steel and cement production, and other industrial procedures. Interestingly, there is other significant importance of coal such as alumina processing plants, paper making firms, synthetic and pharmaceutical ventures (WCA, 2020). The utilisation of coal has been highly linked to power generation (Wrigley, 2013). Study has shown that the effectiveness of power generation from ordinary pulverised coal plant ranges from 35-40% (Na *et al.,* 2015). In addition, most of the power plant stations use steam turbines in which high pressure steam generated from pulverised coal boilers, turn the turbine that drive generators. Several coal deposits that are yet to be harnessed for power generation can be found across Nigeria. The utilisation of the coal deposits for power generation could solve the present and future electricity demand in Nigeria (Ocheri *et al.,* 2017). Nigerian coal is of the bituminous type characterised by low thermoplastic, sulphur and ash content (Chukwu *et al.,* 2016). These properties made it suitable for boiler fuel, production of high calorific gas, domestic heating, briquettes, formed coke and chemicals manufacturing like waxes, resins, adhesives and dyes. These additional properties have also made Nigerian coal ideal for coal-fired power plants (Isaac *et al.,* 2013).

According to Varella (2020), Nigeria has a population of approximately 206 million individuals, but is faced with the challenge of inadequate and constant electricity supply. Accessibility to electricity in the rural and urban areas is about 35% and 55% respectively (Iyiola, 2018). The rise in electricity demand most especially in households will be due to growing urbanization and population growth. Arising from the recent recession, it is expected that the Industrial and commercial demand in Nigeria will increase (Iyiola, 2018). Nigeria, having a 12,500 MW of installed generation capacity, depends, mainly on hydropower and fossil (gas) thermal power sources with 12.5% and 87.5% of production respectively (Olatunji *et al.,* 2018). The actual generation available for final consumers' ranges between 3,500 MW to 5,000 MW (Okubanjo *et al.,* 2020). However, the non-availability of gas to power plant is the major factor responsible for idle power generation plant. It is deemed necessary that government should explore other alternatives to ensure stable electricity such as renewable resource and coal to power projects (Rosen and Dincer, 2003). For instance, government has put a number of programmes to attract companies in developing large coal to power generation and domestic use. Nigeria, having a goal to revitalise the coal mining industry and expand power generation by attracting companies to develop these large coal deposits for power generation and domestic use (Isaac et al, 2013). Energy mix using other available resources for power generation will help in meeting the energy demands of Nigeria. This is achievable by exploring other energy sources like coal to achieve stability in energy supply for the country (Uzoma *et al,* 2012).

Review on other studies shows that works on coal efficiency and thermodynamics as well as emission control of coal power plants were carried out using different methods but the type of coal in used was not specified. However, coal from different countries has different compositions. Coal's composition determines the emission released from its combustion which depends on its location of formation. Nigeria coal deposit considered in this study includes Benue (Owupka), Kogi (Odagbo), and Enugu (Ezimo, Amansiodo and Inyi) Coal deposits. Combustion and emission characteristics of these coal samples have not been well documented. Consequently, this work studies the combustion and emission characteristics (thermodynamics properties) of some selected Nigerian coal samples. This was achieved by using ASPEN PLUS. Simulation of all processes prior to combustion such as grinding and drying was also reported.

2.0 Methodology

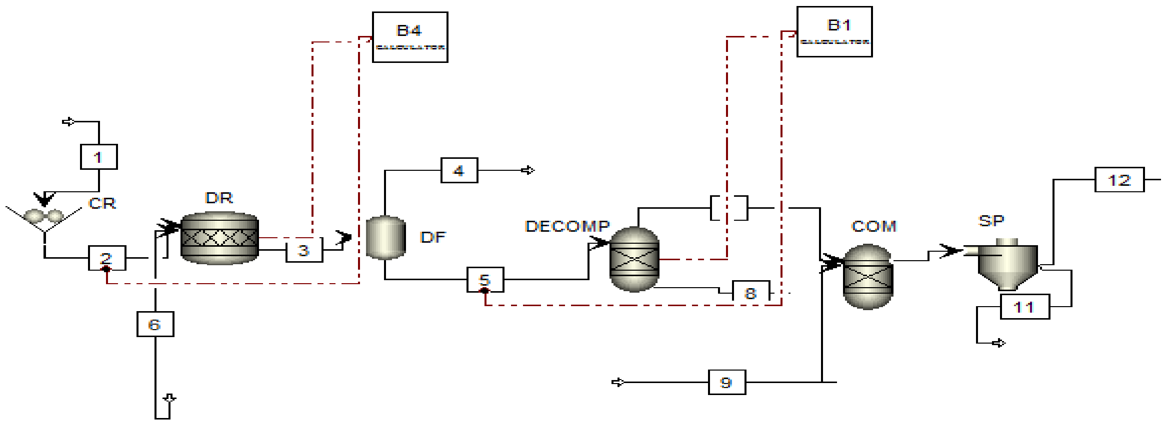
2.1 Coal Samples

Five Nigerian coal samples from Odagbo (Kogi State), Owukpa (Benue State), Ezimo (Enugu State), Amansiodo (Enugu State), and Inyi (Enugu State) of estimated reserves deposits of 250, 75, 156, 1000, and 50 Million tonnes respectively was used in this study. Proximate analysis, ultimate analysis and calorific value as presented by Chukwu *et al.* (2016) were used in this study.

2.2 System Modelling and Simulation procedure

The thermodynamic analysis of a coal power plant as shown in Figure 1 was carried out using a computer code developed by ASPEN for five (5) Nigerian coal samples in this study. All calculations were carried out for ideal conditions. All processes were assumed to be at steady state and steady flow conditions.

ASPEN PLUS stores the estimation methods (calculations) in what is called a "Property Method". The property method is classified into: Ideal property method, Equation of state, Activity coefficient, and Special systems like solids (Al-Malah, 2016; Haydary, 2019). This property method was used to calculate the thermodynamic properties of the coal which includes fugacity, enthalpy, entropy, Gibbs free energy, and volume; and transport properties which include viscosity, thermal conductivity, diffusion coefficient, and surface tension properties for the combustion fluid. The combustion of coal using the pulverization technique was modelled using ASPEN PLUS (Getting started modelling processes with solids). Figure 1 shows the schematic diagram of the coal power plant. The processes for this study are grinding, drying and combustion. The major plant components considered in this study is the combustion chamber.



CR –CRUSHER	C-COMBUSTOR	DR-DRYREACTOR	SP – SEPERATOR	DF- DRY FLASH
DECOMP-DECOMPOSER				

Figure 1: Schematic Diagram of the considered coal power plant.

2.3 Coal Grinding

In modelling the grinding/crushing operation, the particle size distribution for all the coal samples was carried out using the Rosin-Rammler-Sperling-Bennet (RRSB) and the NORMAL distribution function. This model depicts the grinding and screening operation of the coal in which the particle size is independent of the coal sample but depends on the model used.

From Figure 1, stream 1-2 was considered for the grinding process. Coal was supplied at normal temperature and pressure (25^{O}C, 1 atmosphere) to the crusher/pulverizer (CR). The input parameters used was an equidistant user specified Particle Size Distribution (PSD) meshes of 0 to 10 lower and upper limit, and a maximum size unit of 2mm.

The energy (E) required by the crusher is given in Equation (1) and its efficiency (η) in Equation (2).

$$E = K_B\left(\frac{1}{\sqrt{D_2}} - \frac{1}{\sqrt{D_1}}\right) \tag{1}$$

$$\eta = \frac{\text{energy required}}{\text{total energy supplied}} \tag{2}$$

where: E = Energy per unit weight, K_B= bond's work index, D_1 = initial particle diameter, D_2 = final particle diameter

2.4 Coal Drying

From Figure 1, streams 2-5 shows the modelling of the drying process. The temperature of air supplied for drying coal and its mass flow rate determines the amount of water removed from coal. Coal samples contains moisture which must be removed before combustion; else part of the heat of combustion will be converted to remove the moisture content thereby lowering the combustion temperature and burner efficiency (Maurellis and Tennyson, 2003). Coal from the grinding process is mixed with air in this process. Dry air was supplied at 150°C and 1 bar (stream 6) with a mole fraction of N_2 - 0.999, O_2 - 0.001 as given in equation (3). In drying and combustion process, the reactor uses the mass balance equations (equation 4).

$$wet\ coal + Air \rightarrow dry\ coal + wet\ air \tag{3}$$

$$(wet\ air = H_2O + Air)$$

$$\left(\sum_i n_{ij}\right)_{in} - \left(\sum_k n_{ik}\right)_{out} + \left(\sum_n V_{in}\xi_{in}\right)_R = 0 \tag{4}$$

where $\sum_n V_{in}\xi_{in} = n_{i,in} - n_{i,out}$

where: n = mole flow, V = volume, R = gas constant, ξ = molar volume

2.5. Combustion

In this study, the combustion process was modelled using ASPEN PLUS as shown in Figure 1 from stream 5 to 12. Coal from the drying process was decomposed (stream 5-8) using DECOMP before it was combusted. Decomposition involves coal disintegration into its constituents before combustion. Air was supplied at normal temperature and pressure at different equivalence ratio. From this study, it was observed that the coal's combustion exit temperature was determined from the input values of the heat of combustion, mass flow rate of air required for combustion, Utanal and Proximal analysis values as well as prior calculations to combustion. Figure 1 shows that decomposed coal was burnt to gases and solids in the combustor (COM). The combustion products are separated in the SP. Stream 12 is the gas product while stream 11 is the solid product (ash).

The equivalence ratio for the combustion of the five coal samples was calculated using equation 5. The simulation temperature and the amount of gases released at the end of combustion depend on the mass flow rate of air supplied. The chemical formula for the coal samples was determined using the Empirical formula and the balance equation was calculated

ISSN 1596-2644; e-ISSN 2545-5818, www.azojete.com.ng

to determine the mass flow rate of air at different equivalence ratio (φ) for the five coal samples.

$$Equivalence\ ratio\ (\phi) = \frac{\left[\frac{Air}{Fuel}\right]_{stiochiometric}}{\left[\frac{Air}{Fuel}\right]_{Actual}} \tag{5}$$

φ < 1 (lean mixture - excess air is supplied) where the fuel is completely combusted.

φ > 1 (rich mixture - less air is supplied) contains an excessive proportion of fuel after combustion.

In ASPEN PLUS, the Heat of Combustion (HCOMB) is calculated on a dry basis using Equation 6.

The energy balance for steady decomposition state was computed using Gibbs energy (G^o) for steady and equilibrium reactions given in Equations 7 - 9. The rate and heat of reaction in the combustion chamber (Gibbs Reactor) was calculated using the power law (Equations 10 and 11) and the yield is calculated using Equation 12.

$$\text{HCOMB} = \text{Heat of Combustion (wet)}* \frac{100}{(100-\%\ moisture\ content)} \tag{6}$$

$$\left(\sum n_{ij}\right)_{in} - \left(\sum n_{ij}\right)_{out} + \sum \Delta_r H_n \xi_n + Q + W = 0 \tag{7}$$

$$\Delta_r G^o = \Delta_r G^o + RT\ln K_e \tag{8}$$

The equilibrium constant is given as

$$K_e = \prod_i (a_i{}^{v_i})$$

$$G_{mix} = \sum x_i G_i + RT \sum x_i \ln x_i \tag{9}$$

$$r = k\left(\frac{T}{T_{ref}}\right)^{\propto} \exp\left[-\frac{E}{R}\right]\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \prod_i^N C_i{}^{\sigma_i} \tag{10}$$

$$\Delta H_{rxn} = \sum v_i H^o_{f,i} \tag{11}$$

$$\text{Yield} = \frac{\text{amount of product produced}}{\text{amount of feed}} \tag{12}$$

where: n = mole flow, G = Gibbs energy, R = gas constant, W = work, x=mole fraction

k = constant, equilibrium constant, h = Enthalpy, P = pressure, T = temperature,

Q = Heat flow, E= Activation Energy, C=heat capacity ref= reference N=Number of moles,

$\propto$= the law's exponent, ξ = Molar volume, v_i = stoichiometric coefficient (negative for the reactants and positive for the products).

H^o_f = heat of formation for the reactants and products

3. Results and Discussion

Coal undergoes various processes before it produces heat. This includes grinding, drying, decomposition and combustion. The results obtained was considered for producing 300MWe for the coal samples used in this study.

3.1. Grinding/crushing

Result shows that all the coal samples have the same weight fraction and cumulative weight fraction. This is because crushing is a component simulation and it is only concern with the PSD at the outlet and not the thermodynamic properties of the coal when subjected to the same operation conditions.

Figure 2 shows the cumulative fraction in relation to the particle size for both the RRSB and the NORMAL distribution functions. From the figure, for RRSB it can be seen that about 63% of the weight has less than 5µm particle size while for the NORMAL distribution function, 50% of the total weight falls within this range. A significant difference was observed at 4µm particle size. For RRSB about 44% of its weight fraction ranges between 1- 4µm while for the NORMAL distribution only 15% of its cumulative weight falls within this range. This implies that the RRSB has a more uniformly distributed particle size than the NORMAL distribution function. Particles obtained using RRSB model were also observed to be finely grounded. Finely ground coal has more surface area per unit weight than larger particles. This enables the combustion reactions rate to be faster, thereby reducing combustion time. This leads to high heating rates. Grinding also helps to ease the drying process by allowing free flow of air into the grounded coal. Therefore, RRSB was adopted in this study.

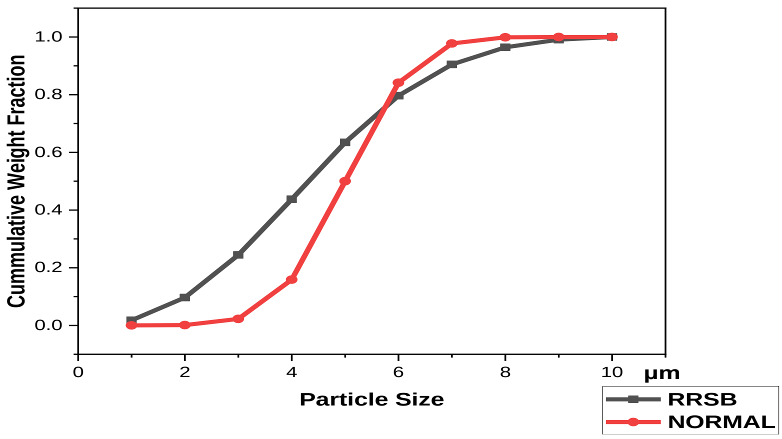


Figure 2: Coal Particle Size Distribution

The power consumption of the crusher is presented in Figure 3. The power consumption for grinding each coal sample depends on the mass flow of coal used at a time. Inyi coal has the highest mass flow of 67.85kg/s requires the highest power consumption of about 23kW while Odagbo has the least value of 13.66kW. Ezimo power consumption is 8% and 3% higher than Owupka and Amansiodo coal. This implies the quantity of coal to be grinded determines the amount of power consumption.

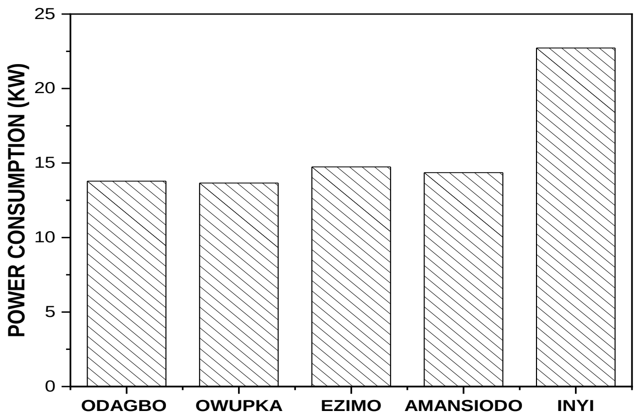


Figure 3: Power Consumption of the Crusher

3.2. Drying

The thermodynamic properties of coal before and after drying were considered in this study.

Figure 4 shows the mass of air per unit mass of coal required to completely remove the moisture for all the coal samples. Coal drying improves plant performance and reduces emission. From the Figure, Odagbo coal having the highest moisture content requires the highest air mass flow of 3.27kg/s while Inyi coal requires the least of 0.9kg/s to dry a unit coal sample. The amount of air required depends on the moisture content in each coal sample.

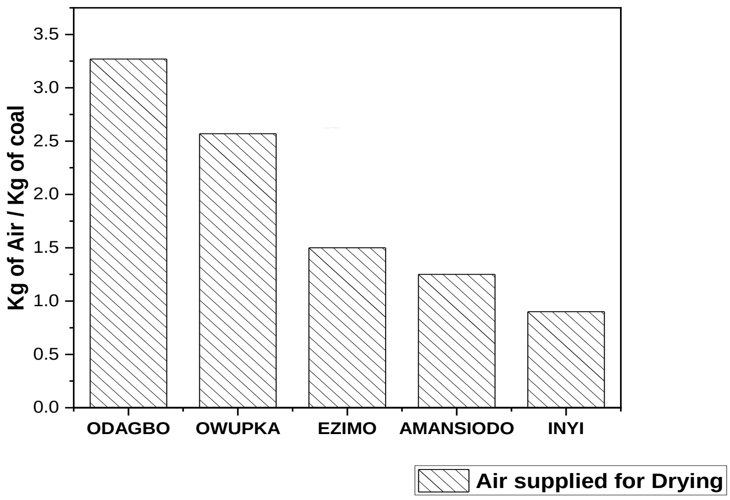


Figure 4: Air Mass Flow for Drying

The amount of thermal energy required for drying was calculated for each coal sample as shown in Figure 5. As expected the heat supplied decreases with coal's moisture composition. However, the heat supplied also depends on the mass flowrate of coal, heat capacity and temperature of air supplied. Odagbo coal requires the highest heat supply because of its high moisture content. Inyi coal requires about 103 kW higher than Amansiodo. This is because of its high coal mass flow compared to all the coal samples. This implies cost of utilities for the plant increases as heat supplied increases.

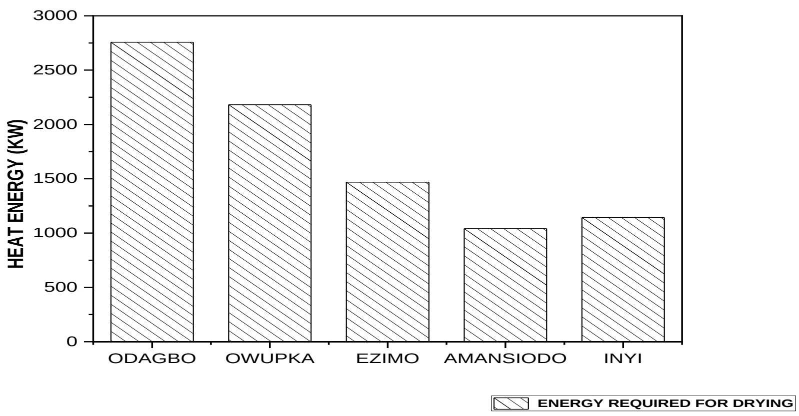


Figure 5: Heat required for drying coal samples

Figure 6 shows the coal exit temperature after drying. The temperature ranges between 36°C and 38°C. The coal water vapour determines the exit temperature (Maurellis and Tennyson, 2003). This implies the higher the water vapour the higher the coal temperature. Odagbo has the highest water vapour of 6 kg/s released because it has the highest moisture content and a high temperature of 38.1°C. While Inyi has 2.6 kg/s water vapour and has the least temperature of 36.7°C.

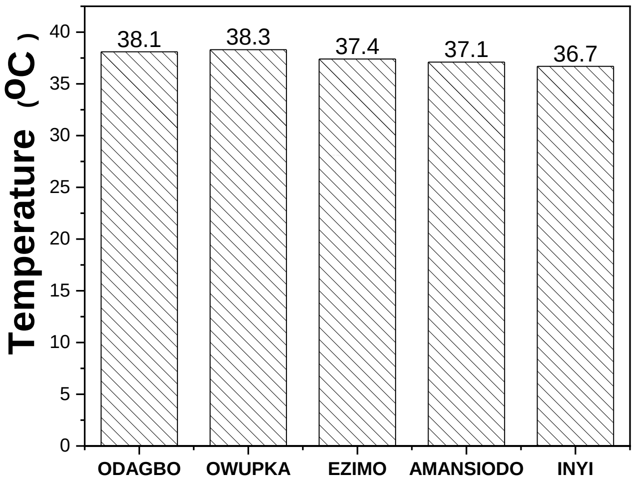


Figure 6: Coal Exit Drying Temperature

Figure 7 shows the mass of coal before and after drying for all the coal samples. It was observed that there is a decrease in the amount of coal after drying. Odagbo coal has the highest decrease of 15% of its actual mass flowrate while Inyi coal has the least decrease of 4% of coal supplied before drying. The inherent moisture for coal samples determines the decrease after drying. This should be considered as it affects the coal's combustion output.

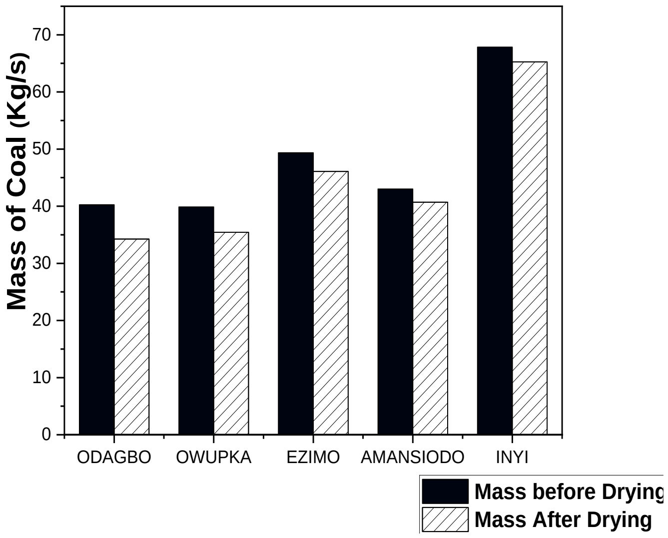


Figure 7: coal mass for drying

3.3. Combustion

The simulated results for combustion at different equivalence ratio (φ) (Air/ Fuel ratio) in relation to the total gas emitted are presented for all the coal sample.

Figure 8 shows the combustion temperature at different equivalence ratio (φ). It shows that temperature decrease as excess air is supplied. Furthermore, it was observed that at stoichiometry (φ = 1) each coal samples has its highest combustion temperature for all the coal samples. Owupka coal sample has a temperature of 2005^{O}C while Inyi coal has the lowest value of 1779^{O}C. This temperature decreases as excess air is supplied for all the coal samples. This is expected and it is due to the cooling of the combustion product by the excess air supplied. Owupka has a temperature of 847^{O}C while Inyi coal has the least at 586^{O}C when air is supplied at 0.3 equivalence ratio (φ). The difference in temperature at the same equivalence ratio (φ) can be attributed to their respective calorific/heating values, ultimate and proximal composition. The temperature values implies the amount of heat energy released during combustion.

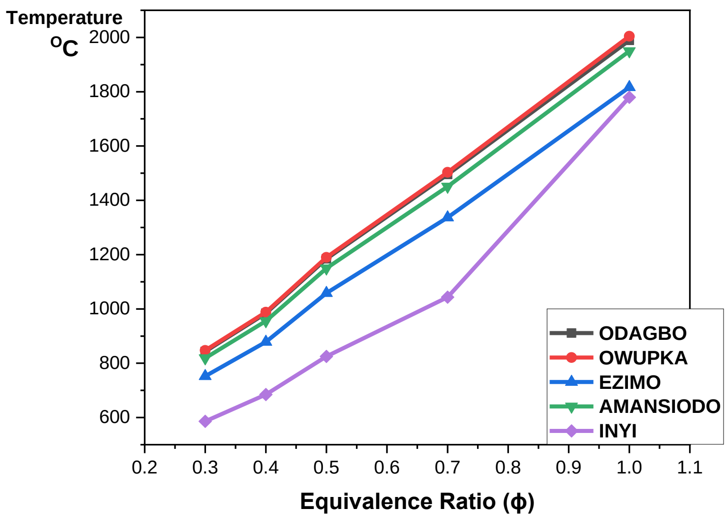


Figure 8: Coal Combustion Temperature

Figure 9 shows the amount of Ash released during combustion for all the coal samples at different equivalence ratio (φ). The amount of ash produced is independent of the equivalence ratio (φ) but depends on the proximal composition of Ash in each of the coal samples. Inyi coal has 30.4% proximal composition and therefore produces the highest amount of ash. For the 300MWe plant, Inyi coal produces about 70 ton/hr while Owupka coal produces approximately 4.7 ton/hr. High ash content lowers the heating value and combustion temperature. This implies high handling cost for ash in an Inyi coal based plant.

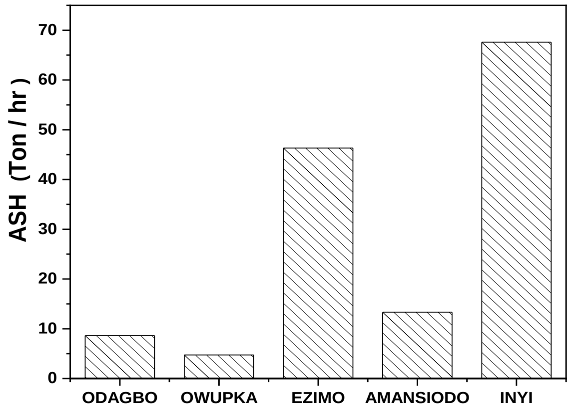


Figure 9: Ash produced

Emission from coal combustion depends on its composition and mass flow of air during combustion. Figure 10 show NO_X emission at different equivalence ratio (φ). Emission of NO_X has both environmental and health hazards. NO_X forms smog and acid rain. High concentrations causes air pollution which are harmful to both plant and animals respiratory organs when inhale directly. NO_X emission is highest at stoichiometry and reduces to zero as excess air is supplied. From Figure 10, decrease in φ decreases the temperature as high temperature has been reported to be favourable to NO_X formation (Miller, 2011). At stoichiometry (φ=1), Amansiodo produces the highest NO_X emission of 5115.7ppm of total gas emission while Inyi coal produces 1267.3ppm of the emitted gases. Inyi coal has the lowest NO_X released during combustion while Odagbo and Owupka coal have close emission values at different equivalence ratio (φ).

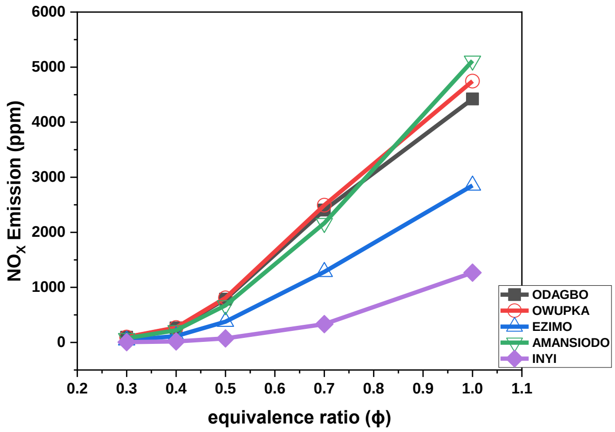


Figure 10: NO_X Emission

Figure 11 shows the CO released at different equivalence ratio (φ). CO is formed when there is no enough air for complete combustion. High concentrations of CO causes air pollution which attacks the respiratory organs and blood haemoglobin. It is also one of the green-house gases that affect the ozone layer. The amount of CO released depends on the amount of air (φ) supplied and the available carbon during combustion. At φ = 1, CO has its highest value for all the coal samples. This is because not all the available carbon is completely combusted to CO_2 at ideal stoichiometric conditions. At stoichiometry (φ =1), Odagbo and Owupka coal samples have similar emissions and produces the highest amount of CO while Inyi produces the least CO at all equivalence ratio values. At φ=0.7, CO converges to approximately zero for all coal samples. It was observed that CO reduces to zero as φ reduces for all the coal samples.

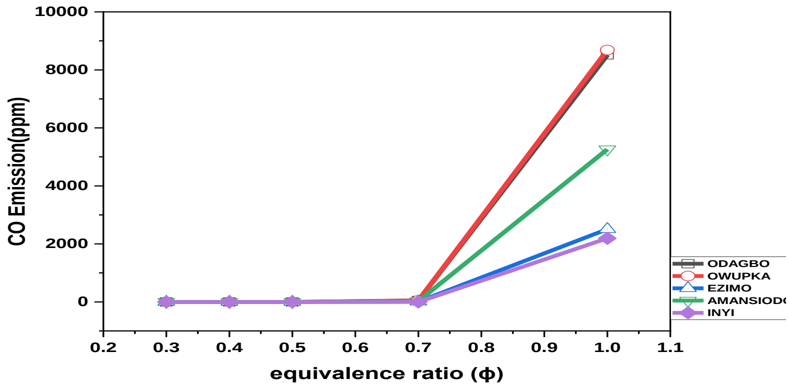


Figure 11: CO Emission

Figure 12 shows the CO_2 emitted at different equivalence ratio (φ). There is an increase in CO_2 emission as φ decreases. CO_2 is formed when complete combustion of carbon in air occurs. The CO_2 emitted depends on the available carbon and oxygen (O_2) during combustion. Excess air supplied converts all the available carbon to CO_2. For Odagbo, Owupka, Ezimo and Amansiodo coal samples, CO_2 produced is independent of the equivalence ratio (φ) from φ = 0.3 to φ = 0.7 beyond which there is an observed reduction of CO_2 with increase equivalence ratio (φ). This depicts that when φ > 0.7, the carbon in the coal could not be completely combusted leaving CO emission as observed in Figure 11. For Inyi coal, CO_2 emission is independent of the equivalence ratio (φ). This implies that at all equivalence ratios (φ), carbon (C) is combustion to CO_2.This is because of its low carbon composition. At all φ values, Odagbo coal sample has the highest CO_2 emission while Owupka coal sample has emission values similar to Amansiodo. Inyi coal has the least CO_2 emission at all φ values. CO_2 causes ozone layer depletion when emitted in high concentrations to the environment thereby causing global warming.

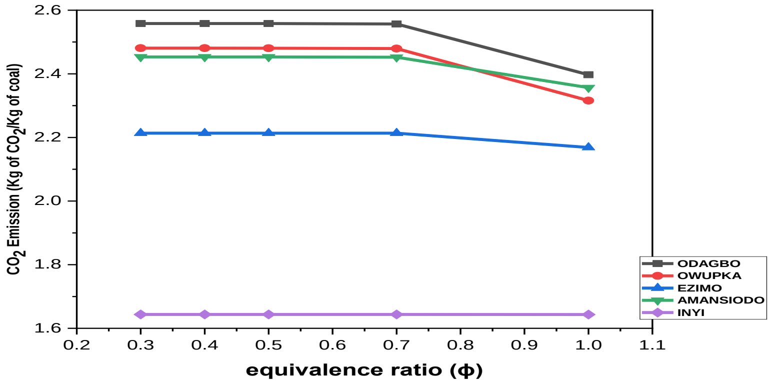


Figure 12: CO_2 Emission

Figure 13 shows the SO_X emitted at different equivalence ratio (φ) for the different coal samples used for this study. All samples have Sulphur composition. The amount of Sulphur emitted during combustion depends on its ultimate percentage composition and the reaction of Sulphur with available O_2 in air. Emission of SO_X has both environmental and health implications. In animals, it causes respiratory disease by reducing lungs functions and other respiratory diseases. In plants, it causes visible injury like losing foliage, becoming less productive and may cause death (World Bank Group, 1999). At equivalence ratio of one (φ =1), high emission values of SO_X compounds are produced which reduces as excess air is supplied. Odagbo, Ezimo and Inyi coal samples have negligible SO_X emission at all φ values. This is because their ultanal composition of sulphur is low. Owupka coal produces the highest SO_X compound which reduces at lower values of φ when excess air is supplied. Amansiodo coal also produces SO_X gas but less than that of Owupka coal. The SO_X in relation to the total gas emission reduces to nearly zero as equivalence ratio (φ) reduces.

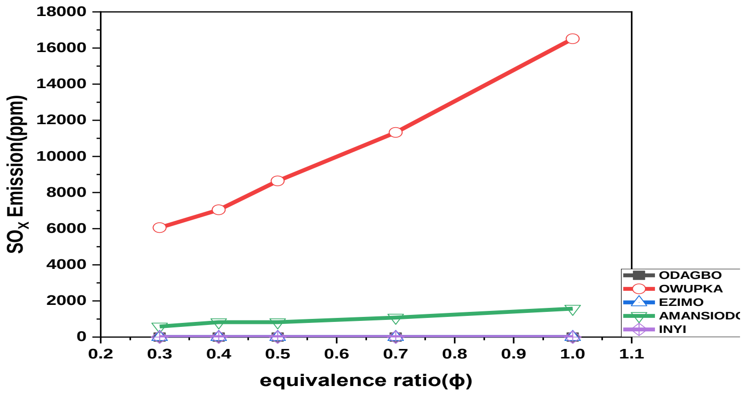


Figure 13: SO_X Emission

3.5. Validation

To validate the results obtained, the operational conditions of a 210 MW Coal Power Plant in North India as presented by Kumar *et al.* (2019) was modelled using ASPEN PLUS. Results obtained for the combustion (Table 1) show similar values with those presented by Kumar *et al.* (2019). From results, it shows the same mass flow of coal was used to produce the same power output. The plant efficiency was however over predicted by 3.91% when compared to the result of Kumar *et al*. (2019). This implies ASPEN PLUS gives a good prediction of an existing plant and its combustion characteristics.

Table 1: Comparison of computed results using ASPEN PLUS and Kumar *et al,* (2019)

Description	Kumar et al. (2019)	Present Study	% Difference
Mass flowrate of coal (Kg/s)	30.55	30.55	0
Net efficiency (%)	35	36.37	3.91
Coal combustion temperature (°**C**)	Approximately 2000	2005 - 1779	Falls within the range of coal combustion temperature

4.0. Conclusion

This study models the combustion characteristics of five Nigerian coal samples using the pulverisation technology in ASPEN PLUS. The RRSB and NORMAL distribution methods were considered when simulating the grinding process. The energy required to dry the coal samples depends on the coals moisture content. For example, Odagbo which has the highest moisture content of 14.9% requires 2800kW to dry. The emission analysis from coal combustion shows that during combustion, the coal's combustion temperature and the emitted gases like CO, CO_2, SO_2 depends on the equivalence ratio (φ) while ash production is independent of the equivalence ratio (φ) but on the coal's proximal content. It was also observed that at φ=1, greenhouse gases emitted were high which reduces as excess air was supplied. Owupka coal is recommended for use because of its high efficiency when compared to the other samples used in this study. Inyi coal has the least temperature of combustion at all values of φ, highest coal mass flowrate and ash production compared to the other coal samples.

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