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Theoretical Air Requirement and Combustion Flue Gases Analysis for Indigenous Biomass Combustion

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Abstract

Rice-husk is one of the most abundant and commonly utilized biomass. It can be used directly to generate primary heating agent in combustion plants. However, emission characteristic of biomass usually vary depending on factors such as the variety of the parent plant, region of cultivation and climatic condition. Moreover, gases emission from biomass combustion could be detrimental to health; hence there is a need for information on the theoretical volume of air and flue gases required for optimal operation of combustion equipment. Thus, this work analyzed the theoretical combustion air requirement and the resulting flue gas volume of the abundant Nerica-rice-husk variety. Rice-husk samples were collected from southwestern part of Nigeria. The samples were characterised for their ultimate and proximate content. Afterward, the combustion analysis was carried out using the elemental composition obtained from the ultimate analysis to determine the theoretical combustion air requirement and the resulting flue gas volume. The proximate analysis result showed the moisture content level, fixed carbon content and ash content value of 10.93%, 12.59% and 18.26% respectively for sample A and 9.80%, 20.76% and 14.81% for sample B. This reveals that Nerica-rice-husk is advisable for use as an alternative energy source in a combustion process. The calculated theoretical volume of air for sample A was 3.69596 (N m^3/kg fuel), while 3.53947 (N m^3/kg fuel) was obtained for sample B. This signifies a slight different between the combustion properties of rice-husk of same variety. It also showed that more quantity of theoretical air will be required to burn sample A compared to sample B, and that sample A will generate little more emissions compared to sample B. Hence, this study reveals the volume of air required for low emission combustion of Nerica-rice-husk in combustion plants.

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1. Introduction

National Ambient Air Quality Standards (NAAQS) by government regulatory agencies are available for the allowable concentration of pollution in the air. These standards apply to emissions from combustion reactors such as fireplace, stoves, furnaces, woodchip and pellet furnace, furnaces with boilers, industrial combustion systems and many others [1]. Biomass such as rice-husk is a good alternative source of energy which is now mostly used in combustion plants to generate primary heating agent in boiler [2]. Emission of more toxic pollutants from the combustion of fossil fuels together with the abundant nature of biomass has switched people attention to burning cleaner

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and renewable biomass [3]. Nevertheless, analysis of flue gases from biomass-fired combustion reactors is highly important in ensuring proper compliance of combustion operation with standards set by the environmental pollution regulatory agencies [2]. Operations where the volume of the emitting flue gases is resulting in high pollutant concentration can be turn off or modified since it could be detrimental to people within the proximity of the emission. Excessive flue gas can also indicate a need for maintenance on the combustion equipment to reduce the emission of toxic gases. The presence of gaseous emission such as carbon monoxide (CO) signifies incomplete combustion and the process can be modified to operate more effectively [1].

Combustion analysis which involves the determination and monitoring of flue gases from solid fuels combustion system is extremely significant in designing and operating combustion equipment. It also ensures safe operating procedure and maximum combustion efficiency [4]. Therefore, this work analyzed the theoretical combustion air requirement and the resulting flue gas volume for the abundant and indigenous rice-husk as an alternative energy source. The rice-husk samples were collected from two different geographical locations in southwestern Nigeria. The samples were characterised for their elemental composition, energy content and proximate content (moisture, volatile, ash, fixed carbon and total carbon content) prior to the combustion analysis.

Characteristic properties of biomass usually vary depending on factors such as the variety of the parent plant, region of cultivation, climatic condition and postharvest processing method. The proximate analysis gives the moisture, ash, volatile and fixed carbon content; ultimate analysis provide information (kg component/ kg fuel) on carbon (%C), hydrogen (%H), nitrogen (%N), sulphur (%S), oxygen (%O) and other elementary chemical composition, and; calorimetry presents the energy content or the heating value of the fuel. The heating value measured in (J/g) is the heat released by the complete combustion of a unit mass of fuel under normal physical conditions, $P_0 = 1.013$ bar and $T = 0^0$C. Heating value is either high heating value (HHV) or low heating value (LHV) depending on the amount of water vapour available in the combustion products. The water vapour is a result of hydrogen oxidation, fuel moisture content and combustion air moisture content. All these characteristic properties determine the combustion characteristic of biomass. Similarly, factors such as the origin of biomass, variety of the parent plant, region of cultivation and climatic condition also affect biomass compositions [5-7].

The use of agricultural waste biomass as fuel has been broadly studied by many researchers [5]. Rice-husk is one of the most abundant and commonly utilized biomass and can be classified as combustible solid waste [5, 6]. During combustion process, variations in the composition of biomass will influence the volume of air required for burning and the volume of the emitted flue gases. Hence, it is important to know the optimum quantity of air that will be needed for maximum combustion efficiency, thus permitting appropriate control of the combustion process. This will culminate in optimum functioning of the equipment, reduce emissions and reduce heat losses [4].

Combustion is a form of chemical reaction process during which combustible elements in fuel react with oxygen in the air to produce large quantity of heat energy. Heat has various applications in industrial processes such as; expansion of gases in cylinder and piston push, environmental heating, boilers, furnaces, power plants and many other systems [4, 7, 8]. Fuel can be fossil or organic and must be able to produce a reasonable amount of heat during combustion with oxygen in the air. A good fuel, under normal condition, will react exothermically with oxygen at high speed and temperature to produce environmentally friendly and non-corrosive flue gases. Also, such fuel must be cheap and abundant in nature. Biomasses are good alternative source of energy which can burn readily in combustion plants to generate primary heating agent in boiler [2]. Burning of biomass and determination of the theoretical combustion requirements necessitate analysis of the biomass to establish:

- the combustible mass,
- ballast, that does not participate in combustion, and
- the energy content of the fuel.

In industrial boiler and many other industrial and household applications, the combustion process involves the reaction between the two major combustion reactants (fuel and air) in a combustion chamber to produce new chemical substances called combustion gases [9]. In most combustion processes, air is the most common and readily available oxidizing agent because it contains free and cheap oxygen while metallurgy and some other specialized system use high-purity oxygen. The oxy-fuel combustion technology is suitable for CO_2 emission reduction [4, 10-12]. Air ratio or excess air coefficient (γ) indicates the nature of the combustion and this determine the composition of the combustion flue gases [4]:

- $\gamma < 1$, indicates incomplete combustion and the products may contain CO, CO_2, SO_2, H_2O and N_2.
- $\gamma = 1$, indicates theoretical or stoichiometric combustion and the products may contain CO_2, SO_2, H_2O and N_2.
- $\gamma > 1$, indicates excess air combustion and the products may contain CO_2, SO_2, H_2O, N_2 and O_2.

1.1. Theoretical combustion

Theoretical or stoichiometric air is the minimum amount of air necessary for the complete combustion of a fuel. This result in no uncombined oxygen in the flue gas and no combustible chemical element such as soot or carbon particles especially for solid fuel. Complete combustion is otherwise called theoretical or stoichiometric combustion. Excess combustion occurs when the amount of air supplied for combustion is more than the theoretical amount needed. A combustion process is termed incomplete when the amount of air or oxygen supplied is less than the theoretical requirement, or when there is an inadequate degree of mixing of sufficient or even excess oxygen. Incomplete combustion can either be mechanical or chemical. Mechanical incomplete combustion is identified by the presence of combustible elements such as soot or carbon in the combustion gases while chemical incomplete combustion contains only the flue gases [4]. Combustion process calculation is mainly aimed at determining:

- the thermal energy resulting from the combustion process,
- the volume of air required for the chemical reactions of the combustible elements in fuel, and
- the volume of flue gas resulting from the combustion process.

Monitoring the volume of air supplied for combustion is highly important. It helps in ensuring that the process is operating with a sufficient quantity of air. Insufficient air will lead to incomplete combustion and unregulated excess air will decrease combustion temperature. This will increase the resulting flue gas volume and then culminates into heat loss [13]. Moreover, monitoring the volume of flue gas will assist in the [4]:

- design and appropriate sizing of the exhaust pipes,
- design and appropriate sizing of the chimney, and
- heat recovery system.

In this work, the combustion air volume and the resulting flue gas volume for a unit mass of rice-husk obtained from two different locations in southwestern Nigeria were determined. This was done by assuming complete combustion and without taking the complex exothermic oxidation of the fuel into consideration. Combustion analysis of the rice-husk samples was achieved using the formulations described under theoretical calculations. These formulations are developed into a web application by Paraschiva et al. [4, 14]. The method is simple and straightforward and also avoids cumbersome calculation that may bring errors.

1.2. Rice-husk

Rice-husk also known as rice hull, can be described as the coating on a grain of rice. It protects the rice grain or seed during the growing season and is formed from materials, such as silica and lignin. Rice-husk is an agricultural by-product of rice-milling industry and belongs to the category of biomass/bioresource material. Each kilogram of milled rice paddy results in roughly 0.28 kg of rice-husk as a by-product. This is about 20-25% of the rice paddy. Singh et al., and Muhammad et al., reported rice to husk ratio to be 0.20 [15, 16]. Therefore, abundance of rice-husk is a function of rice production and the proportion of husk in a paddy.

Husk generation rate in Nigeria is high because rice (Oryza Sativa) is one of the most important staple foods in the country [17]. About 70% of Nigerians feed directly on rice and about 30% feeds on cereal-based foods which are derived from rice [18]. In West Africa, Nigeria is ranked highest as both the producer and consumer of rice [19, 20]. Statistic shows that there is a continuous increase in rice production in Nigeria, especially from the year 2011 due to the government agricultural reform program put in place. This includes Agricultural Transformation Agenda (ATA) and Agriculture Promotion Policy (APP) [21]. According to GEMS4/Coffey International Development LTD report [21], rice is produced in almost all the 36 states of Nigeria and also in the federal capital territory (FCT), Abuja. But majorly, only 18 states represent cumulatively about 80% of the aggregate domestic paddy output in the country [21]. Among these 18 states, preference is given to Ekiti and Ogun state because of their local rice varieties such as Ofada rice. Figure 1 shows the continuous increase in the production of rice in Nigeria from the year 2011.

Rice-husk has numerous uses and among many others, it is a lignocellulosics biomass. It can be used directly in its raw form or converted either into briquette, liquid fuel, tar, and ash before use [22]. Utilization of rice-husk as a feedstock in a biomass combustion system requires prior ultimate, proximate and energy content analysis. That is, in other to optimize the combustion process in adequate reactors, a comprehensive study of the characterization of biomass fuel properties is needed because it remains one of the factors that heavily influence the decomposition of biomass under oxidative condition.

2. Materials and methods

2.1. Materials and instrumentations

Two (2) rice-husk samples of the same paddy variety but from different geographical locations were considered for this research work. Sample A was collected from a local rice mill in Igbemo town, Ekiti state and sample B was obtained from another local rice mill in Ofada town, Ogun state. Both states located in southwestern Nigeria. The rice-husks considered are from Nerica variety. The test materials and instrumentations include; bomb calorimeter, oven; muffle furnace; gas desiccator; digital weighing balance; Cal 2k-Eco calorimeter assembly, pulveriser with Shaker, and atomic absorption spectrometer (AAS).

2.2. Proximate analysis of rice-husk

The rice-husk samples were analyzed for their proximate moisture, volatile, ash, fixed carbon and total carbon content, using American Standard Testing Methods (ASTM) D 3173-87 [1, 20, 21]. The percentage of total carbon in the samples was determined directly by adding the volatile matter and the fixed carbon content.

2.3. Chemical analysis of rice-husk

The Chemical analysis considered for this research work is the ultimate analysis. This determines the elemental composition of C (Carbon), H (Hydrogen), N (Nitrogen), S (Sulphur) and O (Oxygen) in the rice-husk samples (CHNSO test). The information obtained was sufficient to determine the combustion air volume and the resulting flue gas volume for a unit mass of rice-husk.

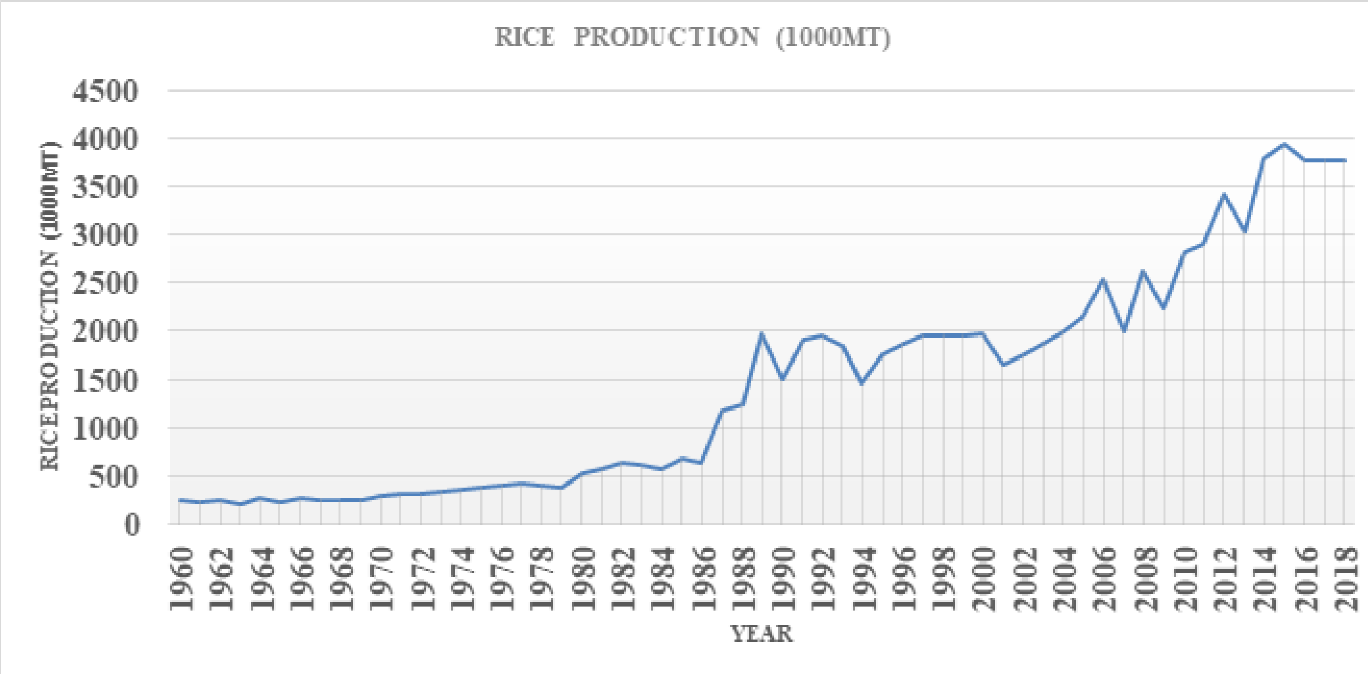

Figure 1. Rice Production Trends in Nigeria from 1960-2018

1. ***Ultimate analysis***:

   Ultimate analysis was carried out to determine the percentage of C (Carbon), H (Hydrogen), O (Oxygen), N (Nitrogen), and S (Sulphur) in the rice-husk samples.

   i *Determination of carbon and hydrogen*: The percentage composition of carbon and hydrogen in the rice-husk samples were determined using ASTM D: 5868-10a procedure [23, 24]. Here, a known quantity of rice-husk sample was burnt in the presence of dry oxygen to ensure that carbon and hydrogen content in the biomass was converted into carbon (iv) oxide (CO_2) and water (H_2O) respectively. Combustion gas from the combustion process was passed over a weighed tubes of anhydrous calcium chloride ($CaCl_2$) and potassium hydroxide (KOH), which absorb the H_2O and CO_2 present in the combustion gas respectively. To this effect, the weight of water (H_2O) and carbon (iv) oxide (CO_2) present in the combustion gas was determined as the increase in weight of $CaCl_2$ and KOH in the tube respectively.

   ii *Determination of nitrogen:* The percentage composition of nitrogen in the rice-husk samples was determined using Kjeldahl's method [23, 24]. Here, a known quantity of pulverized rice-husk sample was heated together with concentrated tetraoxosulphate (vi) acid (H_2SO_4) in a Kjeldahl's flask, in the presence of potassium tetraoxosulphate (vi) salt solution (K_2SO_4) and copper (ii) tetraoxosulphate (vi) salt solution ($CuSO_4$). The reaction converted the nitrogen present in the rice-husk sample to ammonium sulphate and the solution became clear after the entire nitrogen was converted into ammonium sulphate. This clear solution was then treated with 50% NaOH solution to form ammonia which was distilled and absorbed over a given quantity of standard H_2SO_4 solution. Unused volume of H_2SO_4 acid was determined by titrating against standard NaOH solution. This gives the amount of acid neutralized by liberated ammonia in the rice-husk sample. Thus the percentage of nitrogen was determined.

   iii *Determination of sulphur*: The percentage composition of sulphur in the rice-husk samples was determined using ASTM D: 5868-10a procedure [23]. Here, a known quantity of rice-husk sample was heated with Eschka mixture, a combination of 2 parts of Magnesium oxide (MgO) and 1 part of anhydrous Sodium trioxocarbonate (iv) (Na_2CO_3) at 800^0C. This formed a sulphate solution and later precipitates Barium tetraoxosulphate (vi) salt ($BaSO_4$) after treating with $BaCl_2$.

   iv *Determination of oxygen*: The percentage of oxygen in the sample was calculated indirectly by subtracting the sum of the percentage content of carbon, hydrogen, nitrogen and sulphur and from 100%. This is calculated without considering the percentage composition of ash and is similar to the procedure used by Ghetti's [7, 25].

2. ***High heating value of rice-husk***

   Energy content of each sample of rice hush was determined by Bomb Calorimeter (Cal 2k-Eco Calorimeter), in Afe Babalola University, Ado-Ekiti Laboratory (ABUAD) as described by Rominiyi and Adaramola, 2020. Here, 0.5g of dry pulverized rice-husk sample was measured into a clean crucible whose weight has been corrected to zero on the digital weighing balance. And just before the determination of the energy content by the calorimeter, the identification and corresponding weight of the sample were entered into the calorimeter through the connected keyboard. To determine the energy content, a precut of firing cotton was looped over the firing wire of the setup in such a way that the firing wire touches the weighed crucible (containing the sample) placed in the crucible holder. The lid assembly was inserted into the vessel body and the cap down screwed until it touches the top of the lid. This vessel was then placed in the vessel holder in an upright position together with the filling station and filled with oxygen to 3000kPa. After this, the entire vessel was inserted into the measuring chamber and then the lid was closed. This was then followed by the temperature stabilization phase which was carried out for about 10 minutes until the vessel fires automatically at the initial condition of 220 V. The heating value was calculated automatically every 6 seconds taking into account the calibration curve, heating value corrections and sample mass. This also takes place for 10 minutes. Finally, the heating value was displayed on the screen of the calorimeter and taken.

2.4. Theoretical calculations

Stoichiometry combustion air volume and the resulting flue gas volume for a unit mass of rice-husk were calculated according to the procedures given by Paraschiva et al. [4]. These procedures have been developed into a user-friendly web application for easy analysis of the combustion fuel [14]. Utilization of this web application requires knowledge of the analyzed fuel elemental composition, excess air coefficient, absolute humidity of air and the solid fuel flow rate.

1. ***Stoichiometric combustion air***

i *Stoichiometric volume of oxygen*: Stoichiometric volume of oxygen required for combustion when the minimum quantity of air required for combustion is used ($\gamma = 1$) is given as Equation 1:

$$V^s_{O_2} = \frac{22.41}{100}\left(\frac{\%C}{12} + \frac{\%H}{4} + \frac{\%S - \%O}{32}\right)\left(\frac{Nm^3 O_2}{\text{kg fuel}}\right) \tag{1}$$

ii *Stoichiometric oxygen flow rate*: Equation 2 describes the stoichiometric flow rate of oxygen required for combustion

$$Q^s_{O_2} = \dot{m}_{RH} \cdot V^s_{O_2}\left(\frac{Nm^3 O_2}{\text{h}}\right) \tag{2}$$

iii *Stoichiometric volume of dry air*: Stoichiometric volume of dry air required to burn one kilogram of fuel with air having 21% oxygen volume participation is given as Equation 3:

$$V^s_{air} = \frac{V^s_{O_2}}{0.21}\left(\frac{Nm^3 air}{\text{kg fuel}}\right) \tag{3}$$

iv *Dry combustion air flow rate*: Equation 4 presents the flow rate of dry combustion air.

$$Q^s_{air} = \dot{m}_{RH} \cdot V^s_{air}\left(\frac{Nm^3 air}{\text{h}}\right) \tag{4}$$

The correlation given in Equation 1 to 4 is applicable only to dry air. The stoichiometric air volume for wet air is greater than the stoichiometric air volume for dry air due to water vapour content [1]. Therefore, the correlation for wet air involves taking into consideration, absolute humidity, x (kg H_2O/kg dry air) of the air; air temperature, t_{air} (^{o}C) and the relative humidity of air, ϕ_{air} (%). The absolute humidity, x is usually giving as 0.01 kg H_2O/kg for combustion calculation and this corresponds to air at t_{air} =25 ^{o}C and ϕ_{air} =50% according to Paraschiva et al.. But for more accuracy, the absolute humidity can be obtained at known valves of t_{air} andϕ_{air}, using Molliere diagram for moist air. The more accurate absolute humidity can be calculated using Equation 5 and the volume of water vapour in wet air can be determined using Equation 6.

$$x = \frac{0.622\phi_{air}P_s}{(P_b - \phi_{air}P_s)}\left(\frac{\text{kg H}_2\text{O}}{\text{kg dry air}}\right) \tag{5}$$

$$V^s_{H_2O} = \frac{x\rho_{air}V^s_{air}}{\rho_{H_2O}}\left(\frac{Nm^3 H_2O}{\text{kg fuel}}\right) \tag{6}$$

v *Stoichiometric volume of wet air*: Equation 7 gives the stoichiometric volume of wet air required for combustion.

$$V^s_{airW} = \frac{V^s_{air} + x\rho_{air}V_{air}}{\rho_{H_2O}} = \frac{(1 + x\rho_{air})}{\rho_{H_2O}} \cdot V^s_{air} = (1 + 1.61x) \cdot V^s_{air}\left(\frac{Nm^3}{\text{kg fuel}}\right) \tag{7}$$

vi *Wet combustion air flow rate*: The required wet combustion air flow rate for complete combustion can be calculated using Equation 8.

$$Q^s_{airW} = \dot{m}_{RH} \cdot V^s_{airW}\left(\frac{Nm^3 airW}{\text{h}}\right) \tag{8}$$

where

$\dot{m}_{RH}$= Rice-husk (RH) mass flow rate $\left(\frac{\text{kg fuel}}{\text{h}}\right)$

%C, %H, %S and %O= Elemental composition of RH (ultimate analysis).

ρ_{air} = Density of air, usually 1.2925 kg/m^3 at normal state.

ρ_{H_2O} = Density of water vapour, usually 0.804 kg/m^3 at normal state.

2. ***Stoichiometric combustion products***

The following minimum volume of combustion gases will be obtained when the minimum quantity of air required for combustion $'\gamma = 1'$is used.

i *Volume of carbon dioxide in flue gas*: The volume of carbon dioxide obtainable when minimum quality of dry air requirement is used is given by Equation 9.

$$V_{CO_2} = \frac{22.41}{12} \cdot \frac{\%C}{100} \left(\frac{Nm^3 CO_2}{\text{kg fuel}} \right) \quad (9)$$

ii *Volume of sulphur dioxide in flue gas*: The volume of sulphur dioxide obtainable when minimum quality of dry air requirement is used is given by Equation 10.

$$V_{SO_2} = \frac{22.41}{32} \cdot \frac{\%S}{100} \left(\frac{Nm^3 SO_2}{\text{kg fuel}} \right) \quad (10)$$

iii *Volume of water vapour*: The volume of water vapour in the flue gases is the summation of the volume of water vapour from combustion hydrogen and volume of water vapour due to combustion air humidity. The dew point temperature of cooled flue gases depends on the volume of water vapour present in the flue gases.

- Volume of water vapour from combustion hydrogen:

$$V'_{H_2O} = \frac{22.41}{100} \cdot \left(\frac{\%H}{2} + \frac{\%W}{18} \right) \left(\frac{Nm^3 H_2O}{\text{kg fuel}} \right) \quad (11)$$

- Volume of water vapour due to combustion air humidity:

$$V''_{H_2O} = 1.61 \cdot x \cdot V^s_{air} \left(\frac{Nm^3 H_2O}{\text{kg fuel}} \right) \quad (12)$$

Therefore, the total volume of water vapour in flue gas:

$$\begin{aligned} V^s_{H_2O} &= V'_{H_2O} + V''_{H_2O} \\ &= \frac{22.41}{100} \cdot \left(\frac{\%H}{2} + \frac{\%W}{18} \right) \left(\frac{Nm^3 H_2O}{\text{kg fuel}} \right) \end{aligned} \quad (13)$$

iv *Volume of nitrogen in flue gas*: The volume of nitrogen obtainable from minimum quality of dry air and wet air requirement is given by Equation 14 and Equation 15 respectively.

$$V^s_{N_2} = \frac{22.41}{28} \cdot \frac{\%N}{100} + 0.79 \cdot V^s_{air} \left(\frac{Nm^3 N_2 \text{ dry}}{\text{kg fuel}} \right) \quad (14)$$

$$V^s_{N_2 Wet} = \frac{22.41}{28} \cdot \frac{\%N}{100} + 0.79 \cdot V^s_{airW} \left(\frac{Nm^3 N_2 \text{ wet}}{\text{kg fuel}} \right) \quad (15)$$

Nitrogen in flue gas is a result of the elemental flue composition of nitrogen and also the 79% nitrogen composition in the combustion air.

v *Total stoichiometric volume of flue gas*: Equation 16 presents the total stoichiometric volume of flue gas obtainable from dry stoichiometric combustion air while Equation 17 present total stoichiometric volume of flue gas obtainable from wet stoichiometric combustion air.

$$\begin{aligned} V^s_{fg} &= V_{CO_2} + V_{SO_2} + V^s_{N_2} \left(\frac{Nm^3 \text{dry fuel gas}}{\text{kg fuel}} \right) \\ V^s_{fg} &= \frac{22.41}{100} \cdot \left(\frac{\%C}{12} + \frac{\%S}{32} + \frac{\%N}{28} \right) \\ &\quad + 0.79 \cdot V^s_{air} \left(\frac{Nm^3 \text{dry fuel gas}}{\text{kg fuel}} \right) \end{aligned} \quad (16)$$

$$\begin{aligned} V^s_{fgW} &= V_{CO_2} + V_{SO_2} + V'_{H_2O} \\ &\quad + V^s_{N_2 Wet} \left(\frac{Nm^3 \text{wet fuel gas}}{\text{kg fuel}} \right) \\ V^s_{fgW} &= V^s_{fluegas} + V^s_{H_2O} \left(\frac{Nm^3 \text{fuel gas}}{\text{kg fuel}} \right) \end{aligned} \quad (17)$$

vi *Flue gas flow rate*: The total wet flue gas flow rate is given by Equation 18.

$$Q_{fgW} = \dot{m}_{RH} \cdot V_{fgW} \left(\frac{Nm^3 \text{fuel gas}}{\text{h}} \right) \quad (18)$$

This research work used Paraschiva *et al* web application [14] to calculate the theoretical volume of air required for the chemical reactions of the combustible elements in the sampled rice-husk. Also, the application was used to evaluate the volume of flue gas that will result from the combustion process. The elemental composition of the solid fuel samples was obtained from the ultimate analysis, excess air coefficient '$\gamma = 1$' was considered for theoretical or stoichiometric combustion and rice-husk flow rate of 1 kg/hr was used as the calculation basis. The list of all parameters is given in Appendix A.

3. Results and discussion

3.1. Proximate analysis

Moisture content of biomass is expected to be below 10% for a pre-dried sample and about 50% if not dried [7, 14]. Moreover, the volatile matter is expected to be between 65% and 85%, fixed carbon from 7% to 20% and ash content from below 5% to 20% [7, 26]. The details in Table 1 shows that the moisture content of the studied samples is almost 10% which is considered suitable for biomass combustion. Sample B has 9.8% moisture content while sample B has a moisture level that is slightly above 10%. This potential biofuel can be considered suitable for use in biomass boilers because of the low moisture levels.

Furthermore, from the analysis result shown in Table 1, sample A and sample B has 18.26% and 14.81% ash content which are within the recommended range. These low values indicated that at normal combustion conditions the level of particulate matter emission will be low or negligible and the emission from sample B is expected to be slightly below that of sample A [7].

The values obtained for volatile matter, 58.22% and 54.63% for sample A and B respectively are slightly below the range given by so researchers, therefore their reactivity may not be as high as biomass with a volatile matter in the range of 65% to 85% [7, 26]. The higher the volatile matter content the higher the reactivity of biomass [7, 27].

The fixed carbon content of the samples was determined empirically and not experimentally mainly because this study focused more on the elemental composition for the combustion gases analysis. The values obtained for sample A and B as shown in Table 1 is 12.59% and 20.76%. Biomass with such fixed carbon value is advisable for use in combustion process [4]. The moisture content values and the low fixed carbon values obtained indicate that the level of C_xH_y emission will be low and will be generated at a trivial level during theoretical combustion, under proper conditions [7].

3.2. Ultimate analysis

Results obtained for ultimate analysis of the rice-husk samples are shown in Table 2. The major components in solid fuels combustion are carbon, nitrogen and oxygen. Carbon and oxygen react exothermically to generate CO_2 and H_2O, and they also contribute positively to the HHV of fuel [7]. According to studies [7, 26], carbon, hydrogen, oxygen and nitrogen content is expected to range from 47% to 54%, 5.6% to 7%, 40% to 44% and 0.1% to 0.5% respectively. Sulphur is expected to have a value of about 0.1%.

As shown in Table 2, carbon content is 45.08% and 43.99% for sample A and B respectively. These values are approaching the expected value of between 45% and 48% given in the literature. Also, the value obtained for oxygen is 49.27% and 50.64% for sample A and B respectively. These are slightly above the expected value of 40% to 44%.

The values of carbon and oxygen obtained for the characterised rice-husk samples are in contrast with the values obtained by García et al [7]. García *et al* have carbon and oxygen content to be 26.69% and 70.05% which indicate poor energy density, thus showing that biomass characteristic properties vary depending on factors such as the variety of the parent plant, region of cultivation, climatic condition and postharvest processing method.

Nitrogen content (0.84%) in sample A presented in Table 2 is slightly higher than the recommended value of nitrogen in biomass [26], while sample B is within the recommended value of 0.1% to 0.5%. But as the case may be, both analyzed samples are expected to produce a very little or negligible amount of N_2 and NO_x emissions during the combustion process. The majority of the NO_x in waste gases can be attributed to nitrogen present in the combustion air [7].

A low level of sulphur content is highly recommended for biomass combustion because they generate SO_2 which leads to sulphates. Sulphates constitute great problem in heat exchangers. The result presented in Table 2 showed little and negligible amount of sulphur in the samples, thus making the samples suitable as biofuel.

Hydrogen content of both samples as presented in Table 2 slightly agrees with literature. Reports from studies show that hydrogen content of biomass is expected to be between 5.6% and 7% [7, 26]. The energy content of the two samples considered is also similar to those in literature [7]. HHV of sample A, 14.112 MJ/kg is slightly higher than HHV of sample B, 13.326 MJ/kg. The low hydrogen content of sample A (4.76%) and sample B (4.93%) compared with the higher carbon content of the samples (45.08 for sample A and 43.99 for sample B) suggested that carbon contributes more to rice-husk HHV.

3.3. Theoretical calculations

The theoretical volume of air needed for the chemical reactions of the combustible elements in samples of rice-husk, and also the volume of flue gas that will be produced from the combustion process were calculated using Paraschiva *et al* web application [14]. Excess air coefficient of $'\gamma' = 1$ and 1 kg/hr biofuel flow rate were considered for the calculation.

The results obtained are shown in Table 3. The stoichiometric volume of oxygen required for sample A is slightly greater than sample B. Sample A requires 0.76385 (N m^3/kg fuel) while sample B requires 0.74329 (N m^3/kg fuel). The contrast is due to the slight variation in the elemental composition of the two samples, and this variation may be as a result of the difference in the area of cultivation and postharvest processing method. The contrast is slight because both samples are of the same variety and are both from southwestern part of Nigeria. The trend observed in the stoichiometric volume of oxygen required for the samples is also noticed for the stoichiometric combustion air required and wet combustion air flow rate. This is because stoichiometric combustion air required and wet combustion air flow rate both depend on the stoichiometric volume of oxygen. As presented in Table 3, stoichiometric volume of dry air, stoichiometric volume of wet air and wet combustion air flow rate are 3.63740 (N m^3/kg fuel), 3.69596 (N m^3/kg fuel) and 3.69596 (N m^3/h) respectively for sample A, and 3.53947 (N m^3/kg fuel), 3.59645 (N m^3/kg fuel) and 3.59645 (N m^3/h) for sample B. The difference between the stoichiometric volume of dry air and the stoichiometric volume of wet air accounts for the water vapour present in the combustion air. The combustion air flow rate is for a unit mass of fuel per hour.

Analyzed results of the major stoichiometric combustion products are given in Table 3. Carbon dioxide is majorly from the fuel carbon, and the volumes evaluated are 0.84187 (N m^3/kg fuel) and 0.82151 (N m^3/kg fuel) for sample A and B respectively. The volume of sulphur dioxide in the flue gas estimated for both samples are very small, 0.00035 (N m^3/kg fuel) for sample A and 0.00021 (N m^3/kg fuel) for sample B. These quantities are proportional to the level of sulphur in the fuel.

Table 1. Proximate analysis of rice-husk (dry weight basis %)

Rice-husk	Moisture content	Volatile matter	Ash content	Fixed carbon	Total carbon
Sample A	10.93	58.22	18.26	12.59	70.81
Sample B	9.80	54.63	14.81	20.76	75.39

Table 2. Ultimate and calorific value of rice-husk (dry weight basis %)

Rice-husk	C	H	N	S	O^a	HHV (MJ/kg)
Sample A	45.08	4.76	0.84	0.05	49.27	14.112
Sample B	43.99	4.93	0.41	0.03	50.64	13.326

[a] % of O calculated from the difference of C, H, N and S.

Table 3. Rice-husk combustion analysis

Rice Husk	Stoichiometric combustion air [a,b, c] (N m^3/kg fuel)				Stoichiometric combustion products [a,b, c] (N m^3/kg fuel)						
	$Q^s_{O_2}$	V^s_{air}	V^s_{airW}	Q^s_{airW} (N m^3/h)	V_{CO_2}	V_{SO_2}	$V^s_{H_2O}$	$V^s_{N_2}$	V^s_{fg}	V^s_{fgW}	Q_{fgW} (N m^3/h)
Sample A	0.76385	3.63740	3.69596	3.69596	0.84187	0.00035	0.59192	2.88027	4.31441	4.31441	4.31441
Sample B	0.74329	3.53947	3.59645	3.59645	0.82151	0.00021	0.60939	2.79946	4.23058	4.23058	4.23058

[a] $\gamma = 1$, [b] $\dot{m}_{RH} = 1$ kg/hr, [c] $x = 0.01$

Water vapour and nitrogen are inert gas. Water vapour volume is 0.59192 (N m^3/kg fuel) and 0.60939 (N m^3/kg fuel) for sample A and B respectively. Nitrogen gas is 2.88027 (N m^3/kg fuel) and 2.79946 (N m^3/kg fuel) for sample A and B respectively. It is noticed that the volume of nitrogen in the flue gas is greatly influenced by the 79% composition of nitrogen in the combustion air. Finally, the stoichiometry volume of flue gas and the flue gas flow rate is proportional to the stoichiometry volume of wet air and the wet combustion air flow rate. Therefore as presented in Table 3, the stoichiometry volume of flue gas for sample A is 4.31441 (N m^3/kg fuel) and its flue gas flow rate is 4.31441 (N m^3/h), while and sample B has stoichiometry volume of flue gas of (N m^3/kg fuel) and flue gas flow rate of 23058 (N m^3/h).

4. Conclusion

Rice-husks of one of the most commonly planted and abundant rice variety in Nigeria (Nerica-rice-husk) were characterised and evaluated for theoretical combustion air requirement and potential combustion flue gases. The sampled husks were obtained from two different geographical locations within the south-western part of Nigeria. The characterization gives insight into the elemental composition and the energy content of the samples considered. Also, the proximate moisture, volatile, ash, fixed carbon and total carbon content of the samples were determined using standard methods. It was revealed that the difference in the region of cultivation slightly influenced the characteristic properties of the rice-husk.

The low proximate moisture content level of the studied samples which is almost 10% indicated that Nerica-rice-husk is suitable for use in biomass combustion chambers. Ash content value of 18.26% and 14.81% obtained for sample A and sample B respectively showed that at proper combustion condition the level of particulate emission will be low or negligible. The low fixed carbon content of 12.59% and 20.76% obtained for sample A and B respectively also indicated that Nerica-rice-husk is advisable for use in the combustion process. The proximate volatile matter of the two Nerica-rice-husk samples slightly fall below the recommended range of 65% to 85%, therefore the reactivity of the biomass may not be very high during combustion process. The characterization revealed low level of nitrogen and sulphur in both samples, thus at normal combustion conditions the level of NOx and SO_2 will be low. Moreover, there will be a trivial level of C_xH_y emission during proper theoretical combustion of Nerica-rice-husk. Therefore, effective utilization of the abundant Nerica-rice-husk as biofuel will help reduce our dependence on fossil fuels.

Results obtained for the volume of air required for the chemical reactions of the combustible elements in the samples are slightly different. Sample A requires 0.76385 (N m^3/kg fuel) and 3.69596 (N m^3/kg fuel) stoichiometric oxygen and air respectively while sample B requires 0.74329 (N m3/kg) and 3.53947 (N m^3/kg fuel). This showed that more quantity and higher flow rate of theoretical air will be required to burn sample A in combustion reactors such as in steam boiler compared to sample B. The result of the flue gas analysis shows that combustion of sample B will generate less emission compared to sample A. Also, at theoretical combustion of Nerica-rice-husk, the ratio and the amount of emitted sulphur dioxide in the flue gas will be negligible due to low sulphur content of the husk. Also, the ratio and the amount of nitrogen dioxide in the flue gas will be high. The high nature of nitrogen dioxide, 2.88027 (N m^3/kg fuel) and 2.79946 (N m^3/kg fuel) for sample A and

B are due to the inert nitrogen present in the combustion air. Moreover, the combustion of sample A will emit more nitrogen dioxide due to the 0.84% nitrogen content which is more than the recommended nitrogen content for biomass.

This research work indicates a better way of managing the abundant Nerica-rice-husk as an alternative energy source. It can be burn readily in combustion plants to generate primary heating agent. The discrepancies noticed in the results of the two samples considered in this work simply illustrate potential intrinsic risk that is associated with using generally assumed values for the design and sizing of combustion reactors. Such can lead to high calculation errors, thus creating financial and infrastructural problems.

Also, the results obtained for the volume of air required for the chemical reactions of the combustible elements in Nerica-rice-husk together with the volume of flue gas resulting from the combustion process will assist in investigating the operating conditions for minimizing air emissions from rice-husk fired combustion reactors. This will ensure proper compliance of the combustion operation with the standards set by the environmental pollution regulatory agencies. It will also assist in reducing thermal losses from any rice-husk fired combustion system, as theoretical combustion provides the perfect fuel to air ratio, which lower losses and extracts all the energy from a given fuel.

In this work, stoichiometry combustion air volume and the resulting flue gas volume for a unit mass of Nerica rice-husk variety were determined by assuming complete combustion and without taking the complex exothermic oxidation of the fuel into consideration. This can be improved upon in future works by considering the exothermic oxidation of the fuel. Also, a study on excess air combustion analysis of rice-husk which is highly important in attaining better combustion efficiency is recommended.

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Appendix A: Parameters

P_0 = Normal atmospheric pressure
T = Temperature
γ= Air ratio or excess air coefficient

x = Absolute humidity
t_{air} = Air temperature
ϕ_{air} = Relative humidity of air
P_s= Water vapour pressure in saturated wet air
P_b= Water vapour partial pressure
ρ_{air} = Density of air
ρ_{H_2O} = Density of water vapour
$\dot{m}_{RH}$ = Rice-husk mass flow rate $Q^s_{O_2}$= Stoichiometric oxygen flow rate in dry air
Q^s_{airW} = Wet combustion air flow rate
Q_{fgW} = Wet flue gas flow rate $V^s_{O_2}$= Stoichiometric volume of oxygen in dry air
$V^s_{H_2O}$ = Volume of water vapour in wet air
V^s_{air} = Stoichiometric volume of dry air
V^s_{airW} = Stoichiometric volume of wet air
V_{CO_2} = Volume of carbon dioxide in dry flue gas
V_{SO_2} = Volume of sulphur dioxide in dry flue gas
V'_{H_2O} = Volume of water vapour from combustion hydrogen
V''_{H_2O} = Volume of water vapour due to combustion air humidity
$V^s_{H_2o}$ = Total volume of water vapour in stoichiometric dry flue gas
$V^s_{N_2}$= Volume of nitrogen in stoichiometric dry flue gas
$V^s_{N_2Wet}$ = Volume of nitrogen in stoichiometric wet flue gas
V^s_{fg} = Total stoichiometric volume of dry flue gas
V^s_{fgW} = Total stoichiometric volume of wet flue gas
%C, %H, %S and %O= Elemental composition of RH (ultimate analysis)
Nm^3 = Normal cubic meter (Amount of gas present in a volume of $1m^3$ at a temperature of 0 ^{0}C and pressure of 1013 mbar)