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BURNING CHARACTERISTICS AND FUEL PROPERTIES OF OBOMKPA, IHIOMA, AND OGBOLIGBO LIGNITE COALS FROM NIGERIA

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Abstract
Coal utilisation currently accounts for 40% of electricity generation worldwide. With energy demand projected to rise by 50% by 2042, coal-fired power is expected to expand particularly in nations with vast coal deposits such as Nigeria. However, limited scientific data on coal fuel properties and other socio-economic and political factors have hindered progress in Nigeria. Therefore, this study seeks to examine the burning (combustion) characteristics of Obomkpa (BMK), Ihioma (IHM), and Ogboligbo (OGB) lignite coals. It presents insights into the physicochemical properties, thermal degradation behaviour, and characteristic temperature profiles of the coals. The results showed that BMK contains high carbon, hydrogen, heating value but low oxygen compared to IHM and OGB whereas IHM showed the highest volatile matter but the lowest fixed carbon. However, OGB showed poor physicochemical qualities compared to BMK and IHM. The oxidative thermal analyses of the samples resulted in high mass losses and low residuals. The characteristic temperature profiles revealed IHM is more reactive, ignitable, and thermally efficient compared to the BMK and OGB lignite coal samples. Hence, IHM is a good feedstock for gasification, whereas BMK is suited for combustion and OGB for coke formation or coal blending.

Keywords: *Oxidative Characterization; Fuel Characteristics; Lignite Coal; Nigeria.*

1. Introduction

Coal is the most abundant and extensively dispersed fossil fuel worldwide [1]. It is also considered a reliable fuel for the supply of affordable base load energy and offers significant benefits that other fuels cannot currently accomplish around the globe [2]. As a result, coal has become critical to the global energy mix, which presently accounts for over 38% or 8000 TWh of electricity generated from coal-fired power plants [3]. Given this, the coal power industry provides the energy required by billions of consumers worldwide, thereby stimulating socio-economic growth and development as seen in India and China over the years [2,4]. With the demand for energy projected to soar by 50% by the year 2042, coal-fired power generation is expected to expand particularly in nations like Vietnam, Mozambique, and Nigeria. It is predicted that the astronomic growth in energy demand in these nations will expand coal-fired power in the years to come. The discovery of vast new deposits of coal particularly in Nigeria has revived interest in the energy generation. According to estimates, Nigeria has 640 million tons of proven resources and 2.8 billion tons of coal reserves strategically located across Nigeria. The vast majority of Nigeria's coal is located in the lower, middle and upper regions of the Benue trough which extends from the SW to NE of Nigeria's sedimentary basin. Therefore, the establishment of coal power plants in the various geopolitical zones within these sedimentary basins will greatly augment Nigeria's epileptic power supply.

The recent discovery of vast coal deposits in Obomkpa (BMK) in Aniocha-North Local Government Area (Delta State), Ihioma (IHM) in Orlu Local Government Area (Imo State), and Ogboligbo (OGB) in Igalamela-Odolu Local Government Area (Kogi State) have further increased the prospects of coal-fired power generation in Nigeria. Preliminary studies on BMK, IHM, and OGB have revealed the samples are low-ranked coals (LRC) or lignite [5-6] with potential for energy production. Other studies have basically provided estimates of deposits [7-9], physicochemical and mineralogical assessment [10-12], petroleum source rock potential [13-16], or other applications [17]. As a result, there is limited scientific data on the burning (combustion) characteristics and oxidative thermal properties of these lignite coals in literature. Therefore, this study seeks to examine the burning (combustion) characteristics of Obomkpa (BMK), Ihioma (IHM), and Ogboligbo (OGB) lignite coals from Nigeria's sedimentary basin. It will also present comprehensive data on the physicochemical, calorific values, thermal degradation behaviour and characteristic temperature profiles of the samples under mild oxidative conditions. It is envisaged that the findings will provide valuable insights into the fuel properties and possible applications of the lignite coals for the future design, operation and optimisation of coal-fired power or chemical plants in Nigeria.

2. Experimental

The rock samples were acquired from Obomkpa (BMK) in Aniocha-North Local Government Area (Delta State), Ihioma (IHM) in Orlu Local Government Area (Imo State), and Ogboligbo (OGB) in Igalamela-Odolu Local Government Area (Kogi State) all in Nigeria. The samples were subsequently crushed, ground, and sieved into 250 μm sized particles for physicochemical characterisation and thermal analysis. Next, the samples were characterised by ultimate, proximate, and calorific value analyses. The ultimate analyses were performed according to ASTM D5291-16 on the CHNS Elemental analyser (Model: vario MACRO Cube^{TM} GmbH, Germany) to determine the elemental compositions of the samples. Next, the proximate fuel properties were determined through thermogravimetric (TG) analysis according to procedures reported in the literature [18]. The calorific value analysis was performed according to ASTM standard D2015 for determination of higher heating value (HHV) through bomb calorimetry using the combustion calorimeter (Model: IKA C2000, USA).

Next, the burning (combustion) characteristics and thermal degradation behaviour were examined by thermogravimetric analysis (TGA). The TG runs were performed under mild oxidative conditions and controlled by an air flow/purge rate at 20 mL/min through the non-isothermal heating programme of the TG analyser (Model: Shimadzu TG-50 analyser, Japan). For each test, approximately 10 mg of coal was weighed and placed in alumina crucible before the samples were heated at 20 °C/min from 30°C to 800°C. In the end, the TG analyser was cooled down, the raw data retrieved and processed on the Shimadzu Workstation (Version: TA-60WS). Next, the mass loss (%), and derivative mass loss (%/min) was plotted against temperature to obtain TG-DTG plots for the oxidative thermal analysis of the coals. The plots were then analysed, to examine the burning characteristics through its degradation behaviour, thermal reactivity and temperature profile characteristics (TPC), according to the procedures in the literature [19-20]. The TPCs examined in this study are; ignition (T_{ons}), midpoint (T_{mid}), and maximum decomposition (T_{max}), and burnout (T_{off}) temperatures along with mass loss rate (%/min) and residual mass (R_M, %).

3. Results and discussion

The objective of this study is to critically examine the burning characteristics of the lignite coal samples; Obomkpa (BMK), Ihioma (IHM), and Ogboligbo (OGB) from Nigeria. The results are presented in terms of its fuel and burning characteristics.

3.1. Fuel properties

Table 1 presents the fuel properties of BMK, IHM, and OGB lignite coals from Nigeria. The terms; C, H, N, S, O denote the elements carbon, hydrogen, nitrogen, sulphur, and oxygen, respectively. However, M, VM, A, FC, and HHV denote the proximate properties; moisture, volatile matter, ash, fixed carbon and higher heating value, respectively.

Table 1. Fuel characteristics of Nigerian lignite coals

Fuel characteristics	Symbol/Unit	BMK	IHM	OGB
Ultimate analysis	C (wt. %)	50.38	46.80	37.48
	H (wt. %)	5.62	5.39	3.51
	N (wt. %)	0.59	0.64	0.80
	S (wt. %)	0.96	1.52	2.33
	O (wt. %)	42.45	45.64	55.88
Proximate analysis	M (wt. %)	3.63	4.75	3.12
	VM (wt. %)	58.05	69.52	51.43
	A (wt. %)	11.73	2.43	1.03
	FC (wt. %)	26.61	23.30	44.41
Calorific analysis	HHV (MJ/kg)	19.66	19.40	15.55

As observed in Table 1, the coals contain high compositions of C, H, N, O, and S. The highest compositions of C, H and the lowest O were observed for BMK which explains its comparatively higher calorific value (HHV) of 19.66 MJ/kg. Similarly, BMK contains the lowest N and S content which indicates a potentially lower risk of pollutant emissions such as NO_x, SO_x and NH_x during combustion. However, BMK contains the highest ash content of all the lignite coals examined in this study. This could result in significant ash deposition along with the concomitant problems of ash disposal, fouling and agglomeration during combustion. In contrast, the highest N and S content was observed in OGB. The sample also exhibited the lowest C, H, but the highest O which accounts for its low HHV of 15.55 MJ/kg compared to BMK (19.66 MJ/kg) and IHM (19.40 MJ/kg). Lastly, the fuel characteristics of IHM were found to be mid-way between BMK and OGB as observed in the elemental compositions. However, IHM contains the highest and lowest concentrations of VM and FC, respectively. The results indicate IHM is a suitable for coal gasification due to its VM, M and relatively low ash content.

3.2. Burning characteristics

The TG and DTG plots for the oxidative thermal analysis of Obomkpa (BMK), Ihioma (IHM), and Ogboligbo (OGB) lignite coals are presented in Figures 1 and 2.

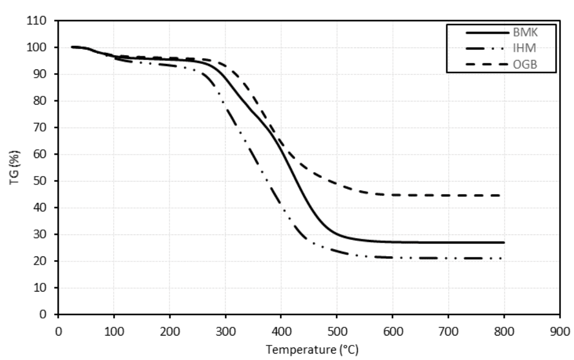

Figure 1. TG plots for oxidative, thermal analysis of Nigerian lignites

As observed in Figure 1, the BMK and IHM coals experienced signification mass loss as evidenced in the downward sloping curves compared to OGB during thermal analysis from RT to 800°C. This demonstrates the burning characteristics, and thermal degradation behaviour was significantly influenced by temperature which resulted in a mass loss during TG analysis. The magnitude of the mass loss for the coals was examined from the temperature profile characteristics (TPCs). The TPCs for the coals deduced from the TG plots in Figure 1 are presented in Table 2.

As observed from Table 2, the T_{ons} for the coals ranged from 250.10°C to 309.45°C. The T_{ons} is the lowest temperature in which a sample undergoing thermal analysis begins to decompose or experience mass loss. The lowest and the highest values for T_{ons} were observed for IHM and BMK, respectively. This indicates that IHM is ignited or begins to thermally decompose at lower temperatures compared to BMK. Hence, it can be surmised that IHM is more reactive (less thermally stable) compared to OGB and BMK based on the reactions conditions examined in this study. The greater reactivity of IHM can be ascribed to its high VM (volatile matter) and lower FC (fixed carbon) as earlier presented in Table 1.

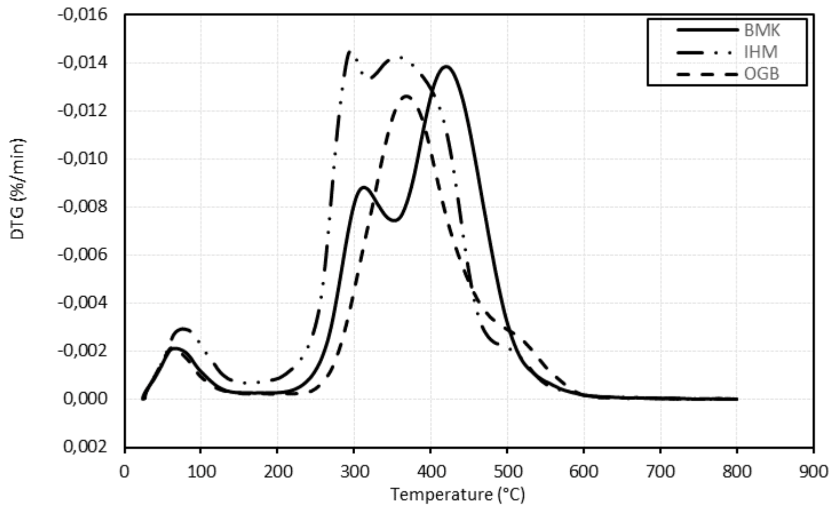

Figure 2. DTG plots for oxidative thermal analysis of Nigerian lignites

Table 2. TG-TPCs for BMK, IHM and OGB lignite coals

TPC Parameter	Symbol, Unit	BMK	IHM	OGB
Onset	T_{ons} (°C)	309.45	250.10	296.37
Mid-point	T_{mid} (°C)	394.32	347.29	375.99
Offset	T_{off} (°C)	480.59	436.53	454.37
Mass loss	(M_L, %)	73.18	78.94	55.51
Residual mass	(R_M, %)	26.82	21.06	44.49

Next, the T_{mid} values for the coals were examined. The T_{mid} is the intermediate temperature of the TG plot during thermal degradation of the sample. As observed, the T_{mid} ranged from 347.29 °C to 394.32 °C. Similarly, the lowest and highest values were observed for IHM and BMK, respectively. Lastly, the burnout temperatures or T_{off} ranged from 436.53°C to 480.59°C. The T_{off} is the temperature in which devolatilization or thermal degradation of volatiles is finalised during TGA. The lowest and highest T_{off} were observed for the IHM and BMK, respectively. Based on the TG-TPCs, IHM is the most reactive coal compared to OGB and BMK.

The mass loss (M_L, %) and residual mass (R_M, %) for the coals were also examined in this study. The M_L (%) is the mass of the sample lost or thermally degraded during TG analysis, whereas the R_M (%) is the mass of the sample remaining at the end of the process. The M_L of the coals was in the range 55.51% to 78.94%. The highest mass loss (M_L, %) was observed for IHM coal whereas the lowest was OGB. However, the R_M ranged from 21.06% to 44.49% for the coals. The highest R_M was observed for OGB whereas the least was for IHM. The results confirm that IHM is the most reactive coal whereas OGB is most thermally stable.

Next, the DTG plots for the oxidative thermal analyses of the coals were deduced as presented in Figure 2. As observed, the DTG plots showed a set of small peaks for derivative mass loss (DTG, %/min) below 200°C for all the coal samples examined in the study. The peaks, denoted as DyP (drying peak), in this range are typically ascribed to drying (or loss of moisture) during thermal analysis. The largest DyP was observed for IHM, BMK, and OGB in decreasing order of magnitude. The size of the IHM drying peak is due to its higher moisture content (4.75 wt.%) compared with BMK (3.63 wt.%) and OGB (3.12 wt.%).

Furthermore, the DTG plots showed another set of larger peaks, denoted as devolatilization peaks 1 and 2 (DvP_1 and DvP_2), in the range 200°C to 600°C for the thermal degradation of the coals examined in the study. The thermal analysis of the OGB coal resulted in one symmetric peak whereas BMK and IHM showed two peaks with different decomposition temperatures. Based on this, the TPCs were deduced to examine the decomposition mechanism of coals based on the DTG peaks as presented in Table 3.

Table 3. DTG-TPCs for BMK, IHM and OGB lignite coals

Parameter	Unit	BMK	IHM	OGB
Drying peak	DyP, °C	64.70	75.87	63.72
Devolatilization peak 1	DvP_1, °C	312.99	295.74	368.50
Devolatilization peak 2	DvP_2, °C	420.14	356.00	No peak

As observed in Table 3, the maximum temperature of the drying peaks (DyP) for the coals ranged from 63.72°C to 75.87°C. The highest DyP was observed for IHM which as earlier stated is due to its higher moisture (M) content compared to BMK and OGB. Due to its higher M, higher energy is required to dry the sample during thermal analysis which accounts for the larger size of its DyP compared to the other samples. Next, the DvP_1 peaks for the coals ranged from 295.74°C to 368.50°C. The DvP_2 peaks observed for only BMK and IHM were between 356.00°C and 420.14°C. In both cases, the lowest peak values were observed for IHM whereas the highest was observed in OGB. Overall, the results confirm that IHM is more reactive compared to the other coals examined based on the TPCs deduced from the thermal analysis. Furthermore, the reactivity of coals was examined from the mass loss during the various stages of the thermal analysis. Based on the DTG peaks and degradation temperatures, the oxidative thermal analysis of the coals occurred in three stages. The range of temperatures was; 25 – 110°C, 110 – 600°C, and 600– 800°C. The corresponding mass losses (M_L, %) during each stage is presented in Table 4.

Table 4. Mass loss during coal decomposition stages

Temperature range (°C)	Stage	Thermal process	BMK (%)	IHM (%)	OGB (%)
25 – 110	I	Drying	3.75	4.65	3.30
110 – 600	II	Devolatilization	69.24	73.99	51.98
600 – 800	III	Coke formation	0.19	0.29	0.23

The mass loss (M_L, %) in stage I ranged from 3.30% for OGB to 4.65% for IHM. As observed, the highest mass loss during the drying stage was for IHM. In comparison, the M_L for the samples is in good agreement with the moisture content in Table 1. In stage II, the M_L ranged from 51.98% (OGB) to 73.99% (IHM). The value observed for BMK is to some degree equivalent to its volatile matter (VM=51.43%) reported in Table 1. However, the M_L values for BMK and IHM observed in Table 4 differ by 11.19% and 4.47% from their VM. The higher values observed for the M_L may be ascribed to degradation or loss of other coal components during thermal analysis. Lastly, M_L during stage III ranged from 0.19 in BMK to 0.29% in IHM. Overall, it can be surmised that the reactivity of the coals is in the order IHM>BMK>OGB based on the M_L data deduced and presented in Table 4.

4. Conclusion

The paper presented new findings on the temperature profile characteristics of three newly discovered lignite coals; BMK (Obomkpa), IHM (Ihioma) and OGB (Ogboligbo) from Nigeria. The coal samples were characterised by physicochemical, calorific value, and non-isothermal oxidative thermogravimetric analyses. The physicochemical analysis results showed that BMK contains high C, H, HHV and low O compared to IHM and OGB. The BMK sample also exhibited the lowest N and S but significantly high ash. The IHM contained the highest VM but the lowest FC. However, OGB showed poor physicochemical coal qualities with comparatively lower values to BMK and IHM. Overall, the oxidative thermal analysis of the coals resulted in a significant mass loss but low residual mass. Based on the temperature profile characteristics (TPC), IHM is more reactive, ignitable, and thermally efficient compared to BMK and OGB. Due to its properties, IHM is a potentially good candidate for energy recovery through gasification. However, BMK will be suitable for combustion whereas OGB is best suited for coke formation or blending with other coals.

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