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Characteristics of Thermal Coal used by Power Plants in Waterberg Region of South Africa

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The current study evaluate the key characteristics of coal used by power stations in the Waterberg region of South Africa as a future alternative to South Africa's well known depletion coal reserves. Eight coals samples used in the current study were supplied by one of South African Power Utility, Eskom power station as received from the nearby Waterberg coalfield in Limpopo, South Africa. Conventional characterization such as proximate and ultimate analysis as well as determination of sulphur forms in coal samples were carried out as per ASTM and ISO standards. The study revealed coal as medium sulphur type coal with pyritic and organic sulphurs accounting for the bulk of the total sulphur. Maceral analyses of coal showed that vitrinite is the dominant maceral (up to 51.8 vol.%), whereas inertinite, liptinite and reactive semifusinite occurred in proportions of 22.6 vol.%, 2.9 vol.% and 5.3 vol.% respectively. The ratio of fixed carbon to volatile matter, commonly referred to as fuel ration which indicates the combustion characteristics of the coal was determined. A correlation between forms of sulphur and total sulphur in medium sulphur Waterberg coals was also established.

1. Introduction

Coal plays a key role in the electricity generation in South Africa and will continue to do so with the combustion of Waterberg coalfield coal in the near future. The depletion of the Witbank and Highveld coalfields as well as the coal quality or mining conditions in the Free State and Springbok Flats coalfields are significant barriers to immediate conventional exploitation (Jeffrey, 2004). Waterberg coalfield is the largest opencast coal mine in the world and operates the world's largest coal beneficiation complex, producing some 18.8 Mtpa of coal products from 38 Mtpa run-of-mine (ROM), using a conventional truck and shovel operation (Hancox and Götz, 2014). Therefore, Waterberg coal should be the basis of South Africa's electricity generation industries' long-term future as per the latter statement. Furthermore, the mine has reserves of 442 Mt and a total resource of 3 000 Mt (Jeffrey, 2005) and consists of a finely interlayered coal-mudstone sequence (Cairncross, 2001). Coal is known to contain a significant amount of sulphur leading to SOx emissions. According to Cheng (2003), sulphur is the most notorious environmental pollutant, which produces SO_2 during combustion. Subsequently, the SO_2 emitted during coal combustion is a principal source of acid rain which poses a health issue and has deleterious effects on the environment. In another case, Zhao et al. (2008) reported that sulphur compounds in coal lead directly to the emission of SO_2 and SO_3 forming sulphate aerosols which leads to corrosion in boiler tubes, pipelines and other machineries during operation. Therefore, sulphur is a major factor in constraining the effective and extensive utilization of coal.

The average sulphur content of South African coals has been reported as quite low by Hancox and Götz (2014). According to Mehliss (1987), washed export grade bituminous coal from the Witbank Coalfield had averaged 0.62 wt.% and the Ermelo Coalfield 1.00 wt.%. Furthermore, anthracite values for the coalfields of KZN for the years 1981–1985 were documented as being 1.26 wt.% (Mehliss, 1987). The distinction between South African coalfields in the context of sulphur content in coal is based on geographic considerations and variations in the mode of sedimentation, origin, formation, distribution and quality of the coals (Hancox and Götz, 2014). However, in the light of impending greenhouse gas emissions reduction programmes, emissions legislative requirements for sulphur emissions have been introduced and adopted by numerous countries including South Africa. Minimum emissions standards stipulates that all installation with design capacity of

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equals or greater than 50 MW heat input per unit, based on the lower calorific value of fuel used shall meet SO_2 requirement limits of 500 mg/Nm^3 and 3500 mg/Nm^3 for new and existing plants respectively (Government Notice No.248, 2010). As a result, reducing sulphur content in coal in order to comply with minimum emissions standards has become a priority.

South African National Power Utility, Eskom historical plants have not been designed with SO_2 reduction in mind as Sulphur was not legislated when these plants were commissioned. However, Eskom has made the decision to employ flue gas desulphurization (FGD) technology for power stations being constructed and where possible to retrofit on the existing power stations. FGD is a technology used to reduce sulphur emissions in coal-fired power utilities by using pulverised limestone in a spray tower to react with SO_2 in the flue gas and remove sulphur as a solid product (gypsum). The FGD scrubbers are estimated to remove approximately 90% of the SO_2 and a significant portion of gaseous chlorides and fluorides that may be present in the flue gases. However, the FGD process results in the production of a FGD wastewater/brine stream which has high concentrations of chlorides, magnesium, calcium, and heavy metals. As a result the FGD effluent cannot be directly re-used somewhere else in the power station. Furthermore, their high capital and/or operating costs, efficiency, reduced availability of the power generating plant, applicability, and the production of significant volume of waste disposal make them expensive for sulphur in coal removal application (Jorjani et al, 2003). The characteristics of coal used by power stations in the Waterberg region of South Africa have not been precisely evaluated in the context of environmental compliance. In order to rectify this situation, we undertook work into evaluating the key characteristics of coal used by power stations in the Waterberg region of South Africa.

2. Materials and Methods

2.1 Experimental Procedure

Eight commercially cleaned (density separated) coal samples used in the current study were supplied by one of the Eskom new built power station, Medupi Power Station as received from the nearby Waterberg coalfield, which is situated some 17 km west of the town of Lephalale, Limpopo Province, South Africa (23°40′18″S 27°31′44″E). Waterberg coalfield also supplies Eskom's coal-fired Matimba Power Station with the same coal. Coal samples were collected from the running unit over an eight-day period.

2.2 ISO 12902:2001 – Determination of Ultimate Analysis

Elemental compositions such as Carbon (C), Hydrogen (H), Nitrogen (N) and Oxygen (O) were determined following the ISO 12902:2001 standard procedure.

2.3 ISO 589:2008 – Moisture analysis in Coal Sample

Moisture in coal sample was performed following the ISO 589:2008 standard procedure.

2.4 ISO 1171: 2010 – Determination of Coal Ash

Coal ash determination was performed following the ISO 1171:2010 standard procedure.

2.5 ISO 562: 2010 – Determination of Volatile Matter

Volatile matter was performed following the ISO 562:2010 standard procedure.

2.6 Fixed Carbon

The solid that remains after the determination of the volatile matter is the whole of the mineral matter and the non-volatile matter in the coal. The non-volatile organic matter is termed "fixed carbon". The fixed carbon value was determined by subtracting the total of the percentage moisture, volatile matter and ash from a hundred.

2.7 ASTM D4239 - Standard Test Methods for Total Sulphur in the Analysis Sample of Coal and Coke

The total sulphur was obtained following ASTM D4239 standard procedure.

2.8 ISO 157:1996 Coal - Determination of forms of Sulphur

ISO 157:1996 standard procedure was applied to the forms of sulphur and the organic sulphur is calculated by difference from the total sulphur obtained by ASTM D4239 standard procedure.

2.9 Maceral Group Analysis ISO 7404/3: 1985

Maceral group analysis involved preparation of coal blocks from particles sized between 300 and 1000 µm using ISO 7404/3:1985 standard procedure.

2.10 Reflectance measurements ISO 7404/5:1985

Vitrinite reflectance is measured as the amount of reflected light from coal particles viewed under microscope on prepared tablets. Reflectance measurements were performed as per ISO 7404/5 standard procedure.

3. Results and Discussions

3.1 Proximate Analysis and Ultimate Analysis

Coal contains a variety of functional groups involving C, O, N and sulphur (S). The classification of the coal is generally done in accordance with the percentage of C, H, and O in the coal. Therefore, elemental compositions such as C, H, S and O were determined and the results are listed as shown in Table 1. Therefore, only C, H and O have been considered and play a vital role as compared to other elements N (1.2 wt.%) of ultimate analysis. Coals containing higher O content of 6.1 wt.% average are more prone to spontaneous combustion. Furthermore, N content of 1.2 wt.% average does not relate to the rank of coal, and therefore it would not have any effect on spontaneous combustion unlike O.

According to Chou (2012), coals are generally termed as low sulphur (≤ 1 wt.% sulphur content), medium sulphur (≥1 to ≤ 3 wt.% sulphur content) and high sulphur coals (≥ 3 wt.% sulphur content) based on their sulphur contents. Sulphur content of 1.15 – 1.49 wt.% range is observed for the coal studied indicating that the coal is a medium sulphur coal type. The sulphur content in medium sulphur coal type derives from the sulphur content of the original plant material forming the peat and sulphate in seawater that flooded peat swamps. The coal ash content ranged between 29 wt.% and 35 wt.%. It must be noted that sulphur and ash contents in coal play a major role in a power generation in terms of boiler sizing and its performance as well as in the release of particulate matter which can contain potentially hazardous elements from coal combustion Saikia et al. (2013). According to Santhosh Raaj et al. (2016), high ash content coal leads to requirement of more number of mills and also influences sizing of primary air fans, air pre-heaters, electro static precipitators as well as coal and ash handling systems. The ratio of fixed carbon to volatile matter, commonly referred to as fuel ratio which indicates the combustion characteristics of the coal for samples 1 – 8 is calculated as 2.37, 2.05, 1.96, 2.17, 2.04, 2.01, 2.08, 2.03 respectively. Measured calorific value (CV) of coal studied is approximately 20.50 MJ/kg as shown in Table 1.

Table 1: Proximate Analysis and Ultimate Analysis

Sample	Carbon (wt.%)	Hydrogen (wt.%)	Nitrogen (wt.%)	Oxygen (wt.%)	Sulphur (wt.%)	Ash (wt.%)	CV (MJ/kg)	Moisture (wt.%)	VM (wt.%)
Sample 1	50.7	3.20	1.10	5.63	1.37	29.0	20.4	2.7	21.4
Sample 2	49.2	2.75	1.22	9.04	1.49	31.3	21.0	2.5	24.0
Sample 3	48.7	2.98	1.12	6.65	1.35	34.5	20.2	2.2	24.9
Sample 4	53.8	3.18	1.14	5.66	1.15	34.8	20.1	2.5	24.8
Sample 5	52.5	3.13	1.14	7.15	1.20	34.2	20.3	2.5	25.7
Sample 6	51.5	2.79	1.58	4.27	1.48	34.0	20.3	1.8	25.6
Sample 7	51.2	3.07	1.18	5.15	1.34	33.4	20.4	2.1	24.6
Sample 8	53.2	3.07	1.11	5.41	1.32	31.0	20.8	2.2	26.2

VM: Volatile Matter; CV: Calorific Value (Measured)

Calculated CV of coal can be estimated based on its C, H, S, and A contents (all on dry basis) as shown in Table 1 as per Eq(1) below:

$$CV = 0.472C \times 1.30H \times 0.190S + 0.107A - 7.52 \quad (1)$$

Eq(1) is proposed from the current study and Figure 1 depicts comparison of measured CV and calculated CV for the studied Waterberg coal. As shown in Figure 1, the standard deviation (s) between the measured CV and the calculated CV for samples 1 – 8 is 1.10, 1.54, 0.41, 1.10, 1.43, 0.59, 0.57 and 0.90 respectively. The standard deviation (s) reiterate that the amount of variation of a set of data values between measured CV and Calculated CV is quite acceptable considering the average standard deviation (s) which confirms that Eq(1) hold for Waterberg coalfield coal studied. Chandra and Mishra (1988) mentioned that a treated coal results in both sulphur content and ash content reduction. Therefore, Eq(1), can be extrapolated on treated Waterberg coals as per Chandra and Mishra (1988)'s claim.

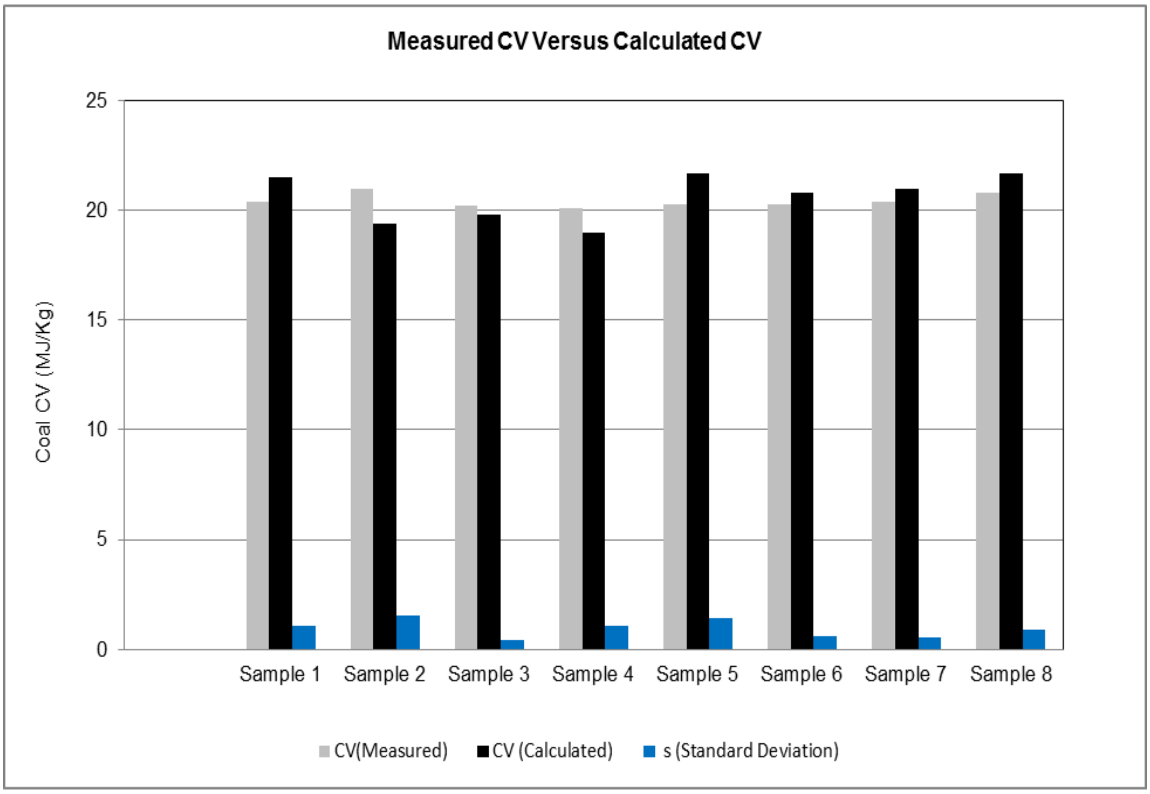

Figure 1: Comparison of measured CV and calculated CV for the studies coal

3.2 Petrographic Study

Macerals are the microscopic constituents of coal. Maceral group analysis of coal samples involved preparation of coal blocks from particles sized between 300 and 1000 µm and the results are reported as average of duplicates in Table 2. Maceral analyses of coals in Table 2 shows that vitrinite is the dominant maceral (up to 51.8 vol.%), whereas inertinite, liptinite and reactive semifusinite generally occur in minor proportions of 22.6 vol.%, 2.9 vol.% and 5.3 vol.% respectively. Earlier studies by Roberts (1988) established that there is a positive correlation between vitrinite and sulphur content in the coal. According to Roberts (1988), vitrinite contains most of organic sulphur in the coal and semifusinite contains significantly smaller amounts of organic sulphur. Liptinite macerals were formed mostly from various protective waxy coatings of plants, Siddhartha Kuma (2013). The liptinite maceral group includes the optically distinct parts of plants such as spores, cuticles, suberine, etc., some degradation products, and those generated during the coalification/maturation process. Mean Reflectance, R_o (max) of 0.76% can be used as a rank indicator for the Waterberg coal.

Table 2: Maceral Analysis of coal

Macerals	Value
Vitrinite [vol.%]	51.8
Liptinite/Exinite)[vol.%]	2.9
Reactive Semifusinite [vol.%]	5.3
Total Inertinite [vol.%]	22.6
Visible Minerals [vol.%]	17.5
Mean Reflectance, R_o%	0.76

3.3 Analysis of Sulphur Forms and Their Distribution in Coal

Samples 1 – 8 were analysed for forms of sulphur in coal and the results are as shown in Table 3. As shown in Table 3, sulphur in coal occurs in various forms such as pyrite, mineral/sulphide sulphur, inorganic sulphates and organic sulphur with pyritic sulphur (FeS_2) being the dominant sulphide mineral in the coal (0.64 wt.%), followed by organic sulphur (0.56 wt.%) then sulphide sulphur (0.14 wt.%) and trace to minor amounts of sulphate sulphur (SO_4) (0.03 wt.%). Because the dominant sulphur is generally pyritic and nodular, additional physical separation technique such as high-density washing can be utilized to reduce much of the sulphur content (as well as the abrasive stone). The organic sulphur found in coal consists primarily of sulphur atoms covalently bonded to aliphatic or aromatic carbon atoms contained in the backbone of the coal macromolecule. According to Saikia et al. (2014), organic sulphur in coals is integrated into the structural matrix in the form of thiols, sulphides and disulphides, and thiophene and its derivatives. The ratio of pyritic sulphur to organic sulphur as a function of the total sulphur content was found to be approximately 1.03 on average.

Relationship between distributions of sulphur forms in coal samples could be established as per Eq.2. The relationship is based on the characterization of total sulphur content in terms of the main coal structure. Therefore, the following relation for the total inorganic sulphur, sulphide/mineral sulphur (S_{IN}), pyritic (S_{PYR}), sulphate sulphur (S_S) and organic sulphur (S_{ORG}) is proposed:

$$Y = m \times S_{TOT} \tag{2}$$

where Y is the form of sulphur [e.g. total inorganic sulphur, sulphide/mineral sulphur (S_{IN}), pyritic (S_{PYR}), sulphate sulphur (S_S) and organic sulphur (S_{ORG})]; S_{TOT} is Total sulphur; and m is the gradient distribution factor.

Using the Eq.2 above, the following gradient factor (m) is established for the current study:

$$S_{IN} = 0.11 \times S_{TOT} \tag{3}$$

$$S_{PYR} = 0.44 \times S_{TOT} \tag{4}$$

$$S_S = 0.02 \times S_{TOT} \tag{5}$$

$$S_{ORG} = 0.43 \times S_{TOT} \tag{6}$$

Distribution factor constant (m) has been established for Waterberg coalfield using Eq.3 – Eq.6 and the results are reported in Table 3. The linear relationship between pyrite, sulphate, mineral/sulphide sulphur and organic sulphur can be used as a rule of thumb for the Waterberg coalfield and may not necessarily be used as it is to other coalfields. The information on the type and distribution on sulphur forms in coal is important in terms of the degree of liberation during any pre-combustion technology selection.

Table 3: Sulphur Forms and Distribution in the coal

Sulphur Forms	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Sulphide Sulphur	0.14	0.16	0.15	0.13	0.13	0.16	0.15	0.15
Organic Sulphur	0.56	0.64	0.58	0.49	0.52	0.64	0.58	0.57
Pyritic Sulphur	0.64	0.66	0.59	0.51	0.53	0.65	0.59	0.58
Sulphate Sulphur	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03
Total Sulphur	1.37	1.49	1.35	1.15	1.20	1.48	1.34	1.32

4. Conclusions

Coal characteristics have an impact on size, efficiency, reliability and availability of boilers as well as emissions in a power plant. Coal used in the current study was a medium sulphur type coal with pyritic and organic sulphurs accounted for the bulk of the total sulphur in coal. Four forms of sulphur - pyrite, mineral/sulphide sulphur, inorganic sulphates and organic sulphur has been characterized. Proximate and ultimate analyses were used to estimate coal calorific value and the average standard deviation of 0.96 was obtained between measured and calculated values. Maceral analyses of coal studied showed that vitrinite is the dominant maceral (up to 51.8 vol.%), whereas inertinite, liptinite and reactive semifusinite generally occur in minor proportions as 22.6 vol.%, 2.9 vol.% and 5.3 vol.% respectively. However, further studies are required to (i) evaluate sulphur content requirements for the Waterberg coalfield coal to comply with the minimum emissions standards of 3500 mg/Nm^3 and 500 mg/Nm^3, (ii) identify a pre-combustion technique that can enable the current Waterberg coal to be treated such that there is no need for post-combustion technique.

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