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# Desirable Coal Quality for a 660 MW Benson Boiler's Full-scale Combustion Tests and Related Emissions

Seshibe S. Makgato*, Nomcebo H. Mthombeni

Department of Chemical Engineering, College of Science, Engineering and Technology, University of South Africa (UNISA), c/o Christiaan de Wet & Pioneer Avenue, Florida Campus 1710, Johannesburg, South Africa.
makgato2001@yahoo.com

Despite the environmental difficulties connected with using this indigenous energy source, there is little doubt that South Africa has enough coal resources to supply future demands in the foreseeable future. The current study presents the results of an experimental investigation using various coal qualities on a 660 MW once-through Benson boiler unit. Conventional coal analyses on all five coal samples studied were carried out following the ISO standard procedures. A boiler's combustion performance and main gaseous pollutants ($CO_2$, CO, NOx and $SO_2$) as a function of the operating parameters and different coal qualities are discussed. The best-performing coal was found to be sample 3 based on emissions, heat losses, and overall efficiency. This study advances our knowledge of how different coal qualities and boiler operating conditions affect boiler efficiency and related emissions.
Keywords: Boiler efficiency, Coal; Coal quality; Combustion; Power plant

## 1. Introduction

South Africa is a major player in coal-based energy production, both locally and internationally. It ranks among the top 10 producers and consumers of coal in the world and is Africa's primary electrical power generator. Particulate matter (PM), nitrogen oxides (NOx), sulphur dioxide ($SO_2$), and carbon dioxide ($CO_2$) are the four criteria pollutants that the country emits the most of, and the majority of these emissions come from the South African energy sector. Because the nation's coal reserves are so small, effective coal use is essential to guaranteeing that supplies persist for a fair amount of time into the long term. The 33 billion tonnes of coal reserves in South Africa, according to Adesina et al. (2022), might be used up until the year 2050 if production continues at the current rate. If managed appropriately, these reserves might significantly strengthen and keep the economy going for several more decades (Adesina et al., 2022).
The once-through Benson boiler technology still has difficulties with regard to ineffective coal combustion, even though it has been in use since the beginning of the 20th century. According to Adesina et al. (2022), improper operating conditions were typically more to blame for boiler inefficiencies. Therefore, little research was done to determine whether fluctuations in coal quality were a reliable cause of these deficiencies. The studies were mostly based on coals from the northern hemisphere, which are of a different quality from coals from South Africa. Coal quality is determined by a number of characteristics, and Falcon and Ham (1988) explain some key terms. The amount of impurities or the composition of the mineral matter that results in the coal's ash content is referred to as "coal grade." Temperature, pressure, and length all affect rank, which is the degree of coal maturity or metamorphosis. Type is an indicator of coal reactivity and denotes the organic makeup of the coal or the original plant matter. The term "condition" describes the degree of weathering or abnormality, such as coal that has been oxidized. As a result, a combination of all the aforementioned components that may be used in a number of applications is referred to as "quality." Park et al. (2019) mentioned that concerns regarding inefficient boilers originate from three basic factors: increased raw material consumption, increased maintenance expenses, and increased pollution, all of which are connected to producing a given amount of heat or steam. Therefore, the study may successfully address these issues mentioned by Park et al. and offer opportunities for the industry to save money by producing steam with less coal per ton.

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South African coals do not fit well with classification systems based largely on northern hemisphere coals, owing to the high but variable concentration of inertinite, mainly semifusinite (Falcon and Ham, 1988). Furthermore, the mineral matter content ranges from fairly high to very high, with a high carbonate content being the most common. Falcon and Ham (1988) mentioned that in common with most Gondwana coals, South African seams are poor in exinite and generally rich in inertinite. According to Falcon and Ham (1988), the difference between South African and European coals was attributed to the fact that South African coals were deposited under very cold, subarctic conditions, very different from the humid, subtropical conditions under which the European coals were formed. The objective of the current study is to establish the desired coal quality for a once-through Benson boiler, optimum combustion efficiency, and associated emissions. To be more specific, once the knowledge of how South African coal quality affects boiler efficiency for Benson-type boilers is thoroughly known and documented, the findings of the current study can be applied at various power generation facilities to considerably improve boiler performance and reduce stack emissions.

## 2. Materials and Methods

### 2.1 Coal samples

The five coal samples utilized in all of the investigations came from various mine stocks that supply power plants. These coal samples were gathered and prepared for various analyses using standardized techniques.

### 2.2 Experimental set-up

The field test was carried out in a 660 MW Benson boiler at a South African coal-fired power plant. The boiler was composed of a housing for a negative pressure furnace, an economizer, and an electrostatic precipitator to collect particulates. All necessary measurement tools were calibrated before the trials were conducted in order to ensure reading accuracy and reduce mistakes. The boiler load was maintained at about 100% (or about 660 MW) of its full load over the study periods, while other operating parameters including coal feeding rates and evaporation rates were constant. Table 1 shows the main operating conditions for a 660 MW once-through Benson boiler.

*Table 1: 660 MW Once-through Benson boiler main operating conditions*

| Properties | Value |
|---|---|
| Coal flow (kg/s) | 91.20 |
| Main steam flow (kg/s) | $45962 \times 10^6$ |
| Superheater outlet steam pressure (MPa) | 26 |
| Superheater outlet  Steam temperature (°C) | 570 |
| Reheated steam flow (kg/s) | 531.4 |
| Feed water temperature (°C) | 248.9 |

### 2.3 Ultimate analyses

Ultimate analyses such as carbon, hydrogen and nitrogen were determined using the LECO-932 CHNS Analyzer in accordance with ISO 12902 standard procedure. The total sulphur was instead measured in duplicates using a Leco S-628 Elemental Analyzer at 1350 °C and following the ASTM D4239-14 standard technique.

### 2.4 Proximate analyses

Moisture, volatile matter, ash, and fixed carbon are determined (by difference) in the proximate analysis. The entirety of the mineral matter and the non-volatile substance in the coal are the only solids left over after the volatile matter has been determined. The term "fixed carbon" refers to non-volatile organic material. The fixed carbon is calculated in the proximate analysis by deducting the combined proportion of moisture, volatile matter, and ash from one hundred. Fixed carbon, therefore, collects all failures from another variable (ash, moisture, and volatile matter). By measuring the mass loss of a coal sample dried in an oven with forced air circulation at a temperature of 150 ± 5 °C, the amount of moisture in the coal was calculated. Ash is the substance that is left over after all of the biological stuff has been burned away. Ash is measured in a furnace at a temperature of 815 ±10 °C using the ISO 1171 (2010) standard procedure. The ISO 562 (2010) standard process is used to determine the volatile matter at a temperature of 1000 °C in a carbonite furnace.

### 2.5 Determination of calorific value

The ISO 1928 (2009) method was used to measure high CV when burning coal samples in a bomb calorimeter.

### 2.6 Ash oxides analysis oxides

The elemental composition of ash oxide was determined using X-ray fluorescence (XRF), in accordance with ASTM D3682-13.

## 3. Results and Discussions

### 3.1 Proximate and ultimate analysis

The percentages of moisture content, ash and volatile matter are shown in Table 2. Fixed carbon is the outcome of the difference. When coal is burned at a high temperature without any air present, thermal breakdown products are released and are referred to as "volatile matter in coal." Volatile matter content can be used to rank coals, establish a basis for buying and selling, or determine burning properties such as a coal's combustibility (reactivity), ease of ignition, and therefore flame stability. Volatile matter content in the five coal samples varies between 23.4% and 26%. Low-volatile coal is less desirable due to its low reactivity, which results in late ignition, unstable combustion and insufficient burnout (Song et al., 2018). Ash, a byproduct of burning coal in the air, is made up of inorganic complexes that were originally contained in the coal's original content as well as by-products of related mineral materials. As a result, the ash yield is frequently used to determine the grade or quality of coal since it gives an estimate of the amount of incombustible particles. Comparing sample 5 to the other samples, sample 5 exhibited a greater ash content of about 30.46 wt.%. High ash levels are undesirable because they can result in the buildup of ash deposits on a coal-fired boiler's heat transfer surfaces, which is one of the key operational problems that must be resolved for stable and efficient coal-fired operations. This viewpoint is supported by research by Park et al. (2019), which discovered that severe ash levels reduced boiler efficiency and, in some circumstances, led to plant shutdowns. The coal samples had a moisture content of between 8.00 and 8.20 wt%, as shown in Table 2. Higher moisture levels in coal are an undesirable component since they lower the fuel's heating value and increase the cost of transportation.

*Table 2: Proximate analysis (wt.%, adb)*

| Properties | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|---|---|---|---|---|---|
| $H_2O$ | 8.20 | 8.00 | 8.10 | 8.00 | 8.15 |
| Ash | 20.30 | 20.50 | 24.20 | 29.26 | 30.46 |
| FC (by diff.) | 45.30 | 48.00 | 42.52 | 40.57 | 41.21 |
| VM | 26.0 | 23.5 | 25.18 | 22.17 | 20.18 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

*Table 3: Ultimate analysis (wt.%, adb)*

| Properties | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|---|---|---|---|---|---|
| $H_2O$ | 8.20 | 8.00 | 8.10 | 8.00 | 8.15 |
| C | 54.45 | 54.60 | 54.78 | 55.12 | 56.70 |
| H | 3.97 | 3.61 | 3.44 | 3.11 | 3.05 |
| N | 1.66 | 1.62 | 1.66 | 1.35 | 1.38 |
| S | 0.77 | 0.81 | 1.14 | 1.50 | 2.09 |
| O (by diff.) | 7.77 | 14.51 | 10.99 | 12.72 | 8.38 |
| CV | 23.18 | 16.85 | 19.89 | 18.20 | 20.25 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

The ultimate analysis (wt.%, adb) for coal samples under consideration is shown in Table 3. According to the range of coal samples studied, the hydrogen content ranges from 3.05 wt.% to 3.97 wt.%. Sample 4 has the lowest nitrogen content (1.35 wt%), whereas sample 3 has the greatest nitrogen content (1.66 wt%). The environmental threat posed by nitrogen, a significant component of coal, is second only to that of sulphur. According to Krzywanski et al. (2018), nitrogen is frequently present in coal, which, when burned, results in NOx. Phiri et al. (2017) came to similar results when they discovered that comparable coal only contains a small amount of nitrogen, around 2% or less.

The percentage sulphur content in the five coal samples was used to classify the coal as low- to medium-sulfur coal within the range of 0.77 to 2.09 wt.% as per the classification of coal. Burning coal with a higher sulphur content (more than 1.50 wt%) is not recommended since it produces a lot of SO2 emissions. Additionally, coal's increased calorific value is impacted by its high sulphur content (Qi et al., 2019).

According to an analysis of the calorific values (CV) of the coal samples, sample 1 had the highest CV, 23.18 MJ/kg, and sample 2 had the lowest CV, 16.85 MJ/kg, showing the amount of heat released during full combustion of these coals. With a higher calorific value, less coal would be needed to produce the same quantity of power, lowering emissions from the power plant and improving the environment.

### 3.2 Ash analysis

When considering how to utilize the ash byproducts of burning coal, understanding ash composition is particularly useful for forecasting how ashes and slags might behave in combustion chambers. When coal is burned, the mineral constituents produce ash that is mostly made up of silicon, aluminium, iron, calcium, magnesium, titanium, manganese, sodium, and potassium oxides, though silicates, sulphates and phosphates are also occasionally found. As a result, in ash research, the primary and minor elements are frequently listed as their oxides. The components of coal ash oxide from coal samples from power plants that were identified using the Philips PW2404 X-ray fluorescence (XRF) spectrometer are shown in Table 4. Heavy metal elements like $Al_2O_3$, CaO, $Fe_2O_3$ and $SiO_2$ as well as trace elements like $TiO_2$, MnO and $P_2O_5$ make up the majority of the chemical components of ash oxide. Table 4 shows that the two most prevalent common oxides are alumina ($Al_2O_3$) and silica ($SiO_2$). $P_2O_5$ and $Na_2O$ are found in small amounts. This is in line with Yusuff et al (2021).'s finding that $SiO_2$ and $Al_2O_3$ (52–62.4 wt% and 22.5–36.7 wt%) affect the chemistry of ash.

*Table 4: Ash mineral analysis (wt.%, adb)*

| Properties | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 58.42 | 58.11 | 58.34 | 58.24 | 58.13 |
| $Al_2O_3$ | 22.01 | 22.23 | 22.34 | 22.26 | 22.46 |
| $Fe_2O_3$ | 3.80 | 3.80 | 3.80 | 3.80 | 3.80 |
| $TiO_2$ | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 |
| $P_2O_5$ | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| CaO | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| MgO | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 |
| $Na_2O$ | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| $K_2O$ | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 |
| $SO_3$ | 5.20 | 5.20 | 5.20 | 5.20 | 5.20 |

### 3.3 Carbon monoxide, carbon dioxide, sulphur dioxide and nitrogen concentration emissions

Carbon monoxide, carbon dioxide, sulphur dioxide and oxides of nitrogen emissions are shown in Table 5. Since they represent the likely levels of nitrogen oxides emitted during combustion, the amounts of nitrogen content among the results of the final study are very significant. The majority of these are nitrogen monoxide (NO), nitrogen dioxide ($NO_2$) and rarely nitrous oxide, together known as NOx. As a result, NOx is generated around the burners in fuel-rich areas of the flames, reaching a maximum concentration of 554 mg/Nm$^3$ in sample 4. In the flame's centre, where temperatures are very high and NOx concentrations are no longer at their highest, the oxygen concentration decreases. At the exit of the economiser, a NOx value of 372 mg/Nm$^3$ is measured for sample 1. The five coal samples studied had roughly identical nitrogen fractions, with sample 2 having the lowest value at 333 mg/Nm$^3$ and sample 1 having the highest value at 372 mg/Nm$^3$. Therefore, sample 1 is expected to contribute a greater proportion of fuel NOx to the total NOx emissions. Similarly, a comparison of the emissions factor predicted at various coal qualities for the five samples is shown in Table 5. Sample 1 had the lowest carbon monoxide concentration (310 ppm), while sample 2 had the highest (367 ppm) carbon monoxide concentration. The trends agree very well with the benchmark data. Several methods have been put forward for the capture, storage, and use of carbon for various purposes, such as the creation of sustainable energy. For example, a range of methods is used for the separation of $CO_2$, such as absorption and adsorption. Carbon monoxide is the most common gas that serves as an indicator of energy losses emanating from deficient combustion. Boiler operators should strive to keep carbon monoxide within the range of 310 – 367 ppm (0.3%–0.4%), which corresponds to below 2% heat loss which is within the boiler design specification. According to Table 5, coal samples with sulphur contents (in wt.%) of 0.77, 0.81, 1.14, 1.50, and 2.09 produced $SO_2$ emissions (in mg/Nm$^3$ @ 6% $O_2$) of 1662, 1749, 2460, 3237 and 4510, respectively. Table 5 makes it evident that sulphur content in coal samples causes $SO_2$ emissions to increase linearly, indicating that the volume of sulphur compounds emitted is precisely proportionate to the amount of sulphur contained in the parent coal. The emissions of $SO_2$ in Makgato and Chirwa's (2017) findings and the findings of this investigation are in good accord.

Low sulphur fuels and various technologies, such as flue gas desulphurization (FGD), wet flue gas desulphurization (WFGD), dry sorbent injection (DSI), and bio-desulphurization technologies, can be used to reduce SOx emissions (Asghar et al., 2021). It is crucial to note that the reduction in flue gas exit temperature coincided with the reduction in carbon monoxide, carbon dioxide, sulphur dioxide and nitrogen concentration emissions from the furnace exit (64 m) via the economiser inlet (54 m) and economiser outlet (38 m) in line with the decrease in temperature of flue gas exit temperature. The most air leaks were found where the economizer outlet meets the boiler furnace, within the range of 20.22 and 24.90, while the least air leaks were found between the boiler furnace exit and the economizer inlet.

*Table 5: Boiler efficiency, main gaseous pollutants, leakages and oxygen content in flue-gas*

| Properties | Unit | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|---|---|---|---|---|---|---|
| **Furnace Exit (Level = 64 m)** | | | | | | |
| Flue Gas Temperature | (°C) | 542 | 581 | 583 | 582 | 581 |
| Oxygen Concentration | % | 3.05 | 3.04 | 3.08 | 3.04 | 3.03 |
| Carbon Dioxide Concentration | % | 16.05 | 15.63 | 15.92 | 15.84 | 15.97 |
| Carbon Monoxide Concentration | ppm @ 6% $O_2$ | 4763 | 4639 | 4382 | 4272 | 4541 |
| Oxides of Nitrogen Concentration | mg/Nm$^3$ @ 6% $O_2$ | 540 | 536 | 542 | 554 | 553 |
| Sulphur Dioxide Concentration | mg/Nm$^3$ @ 6% $O_2$ | 2014 | 2302 | 2982 | 3924 | 5467 |
| **Economiser Inlet (Level = 54 m)** | | | | | | |
| Flue Gas Temperature | (°C) | 425 | 426 | 420 | 424 | 426 |
| Oxygen Concentration | % | 3.10 | 3.13 | 3.11 | 2.98 | 3.14 |
| Carbon Dioxide Concentration | % | 15.30 | 15.32 | 15.52 | 15.43 | 15.66 |
| Carbon Monoxide Concentration | ppm @ 6% $O_2$ | 3572 | 3479 | 3287 | 3270 | 3607 |
| Oxides of Nitrogen Concentration | mg/Nm$^3$ @ 6% $O_2$ | 499 | 451 | 427 | 431 | 436 |
| Sulphur Dioxide Concentration | mg/Nm$^3$ @ 6% $O_2$ | 1802 | 1896 | 2669 | 3511 | 4892 |
| **Economiser Outlet (Level = 38 m)** | | | | | | |
| Flue Gas Temperature | (°C) | 334 | 337 | 329 | 328 | 332 |
| Oxygen Concentration | % | 3.14 | 3.13 | 3.38 | 3.09 | 3.30 |
| Carbon Dioxide Concentration | % | 14.84 | 14.63 | 14.51 | 14.84 | 14.65 |
| Carbon Monoxide Concentration | ppm @ 6% $O_2$ | 310 | 367 | 356 | 331 | 339 |
| Oxides of Nitrogen Concentration | mg/Nm$^3$ @ 6% $O_2$ | 372 | 333 | 364 | 338 | 341 |
| Sulphur Dioxide Concentration | mg/Nm$^3$ @ 6% $O_2$ | 1662 | 1749 | 2460 | 3237 | 4510 |
| **Boiler Efficiency** | % | 98.79 | 80.08 | 99.04 | 98.92 | 98.94 |
| **Leakages** | | | | | | |
| In-furnace Leakage | % | 2.40 | 2.43 | 2.46 | 2.44 | 2.49 |
| Between the Furnace exit and Eco-inlet | % | 1.12 | 1.10 | 1.11 | 1.13 | 1.12 |
| Between Eco-inlet and Eco-Outlet | % | 18.30 | 18.60 | 19.11 | 19.18 | 19.30 |
| Between Eco-outlet and Furnace | % | 20.22 | 22.45 | 23.10 | 24.33 | 24.90 |

### 3.4 Boiler efficiency

The amount of coal's chemical energy that is converted into thermal energy is known as boiler efficiency. It is important to note that efficient fuel combustion and efficient heat transmission from the "fuel mass" to the surfaces that convert water to steam are two aspects of the boiler efficiency concept. The combustion efficiency was calculated using the heat loss method in accordance with British Standards, BS 845-1 (1987). The quantity of heat delivered to the water or steam in the boiler is measured by the boiler's combustion efficiency, and the stoichiometric air is the amount of air required for full combustion, as given in Eq. (1):

$$\eta = \frac{(\text{Heat in Steam})}{(\text{Heat in Fuel})} \tag{1}$$

Table 5 displays boiler efficiency for five coal samples under consideration. As can be seen in Table 5, the boiler with sample 3 has a 99.04% efficiency, which is much greater than sample 2's 80.08% efficiency. Although coal sample 5 has the highest calorific value and the second-best boiler efficiency, its SOx emissions, at 4510 ppm, are too high. Therefore, environmental rules restrict the use of samples 4 and 5 due to their significant SOx emissions, despite the boiler efficiency still being good. The results of this study showed that for 660 MW Once-through Benson boiler management measures should be operated according to their actual emission characteristics based on the coal quality. According to Tu et al. (2019), the boiler's five main components: bottom ash heat loss, incomplete combustion in the flue gas, heat exchange via the outer wall of the boiler, unburned carbon in the bottom ash, and stack loss are where the majority of the heat is lost.

## 4. Conclusions

The effect of coal quality on a once-through Benson boiler and its related optimum combustion efficiency as well as related emissions were considered in the present study. Based on the research and analyses carried out, it was determined that: The quality of coal proved to significantly influence the combustion performance and its associated main gaseous pollutants. For example, the outcomes of the boiler efficiency test revealed that sample 3 had the best performance with a boiler efficiency of 99.04%, whereas sample 2 scored worse with a boiler efficiency of 80.08%. In addition, sample 3 has a desirable $SO_2$ emissions value (in mg/Nm$^3$ @ 6% $O_2$) of 2460. However, the NOx concentration of 384 (in mg/Nm$^3$ @ 6% $O_2$) is almost at the borderline. Carbon monoxide (ppm @ 6% O2), an indicator of energy losses resulting from insufficient combustion, for sample 3 is below the borderline, which is desirable. The findings of this study aid in a thorough evaluation of the effects of different coal properties on boiler performance and its related emissions.

**Nomenclature**

C – fixed carbon, wt.%
CV – calorific value
VM – volatile matter, wt.%
C – carbon, wt.%
H – hydrogen, wt.%
N – nitrogen, wt.%
wt.% - weighted percentage
adb – air dried basis
S- sulphur content, wt.%
O – oxygen, wt.%

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