Abstract

Coal quality, which has deteriorated in South Africa, is a major factor for sugar mills to consider especially as co-generation becomes a growing concern. Coal quality is especially essential in sugar mills reliant on coal for refining and, as is often the case, the proximate analysis cannot be used as the solitary predictor of boiler performance. Abundant literature is available for pulverized coal combustion in boilers, with validated details on devolatilisation rates, volatile reaction kinetic rates, carbon monoxide reaction rates and char burnout rates. This level of detail is required to successfully simulate boiler performance with CFD simulations.

Testing equipment to determine these parameters is expensive and requires numerous tests to achieve a confident result. The results from these tests also need careful consideration to be implemented in a fixed bed model as all parameters may not be relevant. This paper details a novel testing procedure and fixed bed reactor where parameters of fixed bed combustion can be determined. These parameters are linked with a CFD model of the reactor and subsequently used to predict performance in large industrial boilers. Following a standardised methodology for testing, a database of various coal qualities and their area of origin have been established.

Keywords: *fixed bed combustion, computational fluid dynamics, particle size distribution*

A coal classification to evaluate boiler performance, using computational fluid dynamics and a fixed bed reactor

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Coal Classification

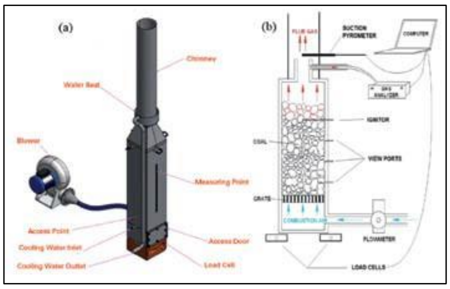
Introduction

The advantages of using CFD models in predicting combustion behaviour and temperatures are ample and well-explained by (Du Toit and Van Der Merwe, 2014). The objective of this study was to determine if two coals, with similar proximate analyses, could be differentiated with a new experimental testing method. Additionally, the approach was to simulate the combustion behaviour of the two coals with CFD, using the geometry and boundary conditions of the experimental setup. The goal was to determine empirical constants form the CFD analysis to simulate the combustion in an industrial watertube boiler. Fuel conversion, O2, CO and temperatures were used as parameters to determine the effectiveness of combustion solutions. Details on CFD model settings are given by Du Toit and Van Der Merwe, 2014.

General

The experimental setup consisted of a fixed bed reactor which is water cooled and loaded with a fixed amount of coal, and ignited, as depicted by Figure 1(a).

Figure 1: (a) Three-dimensional rendering of experimental setup (b) a sectional side view of the experimental setup



Several parameters are recorded as a function of time. These include:

- Mass loss of coal;
- Flue gas temperature leaving the furnace;
- CO and O2; and
- Pressure drop over the grate.

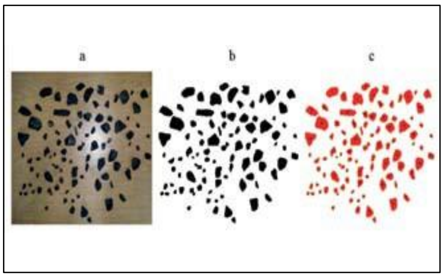
The outcome of the experimental setup are:

- Mass reduction curve;
- Ash content as percentage of initial mass;
- Particle size distribution; and
- Vertical burn-down rate

Procedure

The coal samples are prepared based on particle size to reduce the influence thereof in the combustion process. The coal samples are sieved to achieve the desired size distribution. A final check is done with PSD (particle size distribution) software, as shown in Figure 2, to check that samples have a similar PSD.

Figure 2: (a) Original image (b) Image after filtering (c) Image edge detection and PSD software



The coal samples are then loaded into the combustion chamber where the top 25mm of coal is ignited and combustion of the coal is vertically down. CO and O2 are recorded with a gas analyser. Temperature is measured at a single point with a suction pyrometer, as depicted by Figure 1b. The change in mass is measured by ultra-sensitive load cells.

Experimental Test Results

Two coals were tested for this case, Coal-A and Coal-B. The laboratory analysis for the two coals is given in Table 1. There are differences in the analyses of the two coals, with the most notable difference being in volatiles.

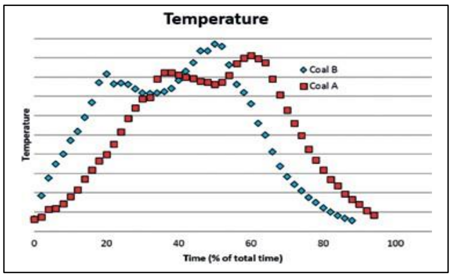
Table 1: Ultimate and proximate analysis of the two coals [%]

	Coal-A	Coal-B
C	69.20	70.60
H	3.44	4.15
O	4.61	6.64
N	2.05	1.80
Fixed Carbon	60.9	54.8
Volatiles	19.8	29.2
Moisture	1.7	2.9
Ash	17.6	13.1

The differences in the combustion were obvious with Coal-B igniting quickly and resulting in a faster burnout. This rapid increase in temperature in Coal-B, as depicted by Figure 3, can be attributed to a higher volatile content which led to a quick rise in combustion temperature.

From the temperature curves, three distinct phases of combustion can be identified i.e. ignition phase, stable phase and char burnout phase. The peak temperatures of the two coal types correspond well, indicating that the combustion temperatures are similar.

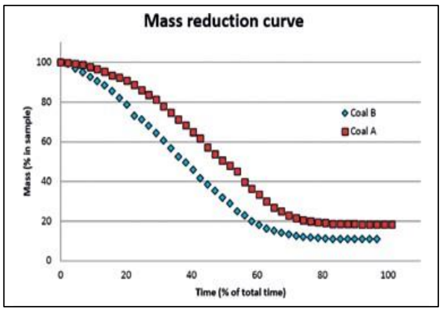
Figure 3: Temperature curves over time, where 100% corresponds to the total time of the longest test



in mass, accelerates the combustion to reach stable condition in Coal-B 73% earlier than in the case of Coal-A. The stable combustion phase is, however, similar in both the coals as depicted by the linear gradient in Figure 4.

The mass reduction curve also illustrates the difference in ash contents in the two coals. Coal-A had 18% residual mass compared to the 11% residual mass for Coal-B. These values correspond well to the values as determined by laboratory analyses, given in Table 1 as 17.6% and 13.1% for Coal-A and Coal-B, respectively.

Figure 4: The mass reduction curves of the two coals over the duration of the test



The oxygen and carbon-monoxide curves are depicted by Figure 5 and 6 respectively. From these curves it is evident that the onset of stable combustion occurred quicker with Coal-B compared to Coal-A.

Figure 5: O_2 during the tests for the two coals

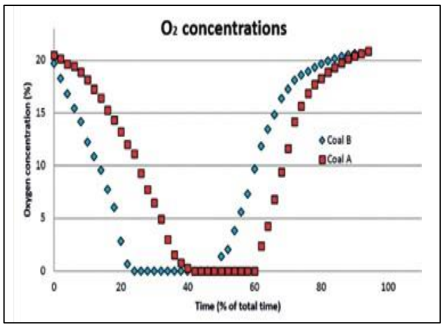


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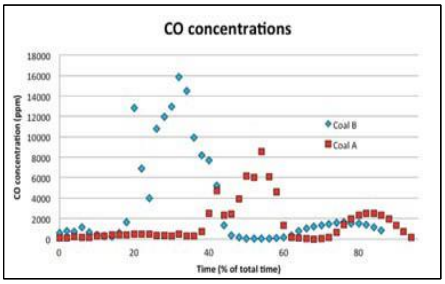
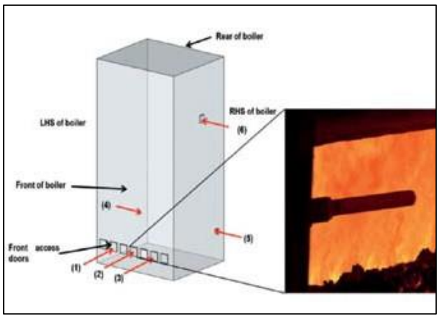
Figure 6: CO concentration of the two coals



Site measurements results

These two coals were also tested on a 100 t/h steam boiler. The boiler is equipped with coal flingers on the front wall and a CAD stoker. During the tests, temperature measurements were taken at various locations on the boiler as depicted by Figure 7.

Figure 7: Temperature measurement locations as shown by the arrows



The temperature measurements taken with a suction pyrometer showed that Coal-B had significantly lower temperatures at the front of the boiler (points 1–3), as shown in Table 2. This is an indication of more complete combustion since Coal-A had notably higher temperatures at the same points.

Table 2: Temperatures at the various locations in the boiler [°C]

Position	Coal-A	Coal-B
1	1240	720
2	1170	832
3	76	793
4	1165	1200
5	970	948
6	970	911

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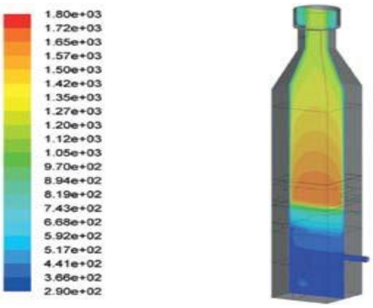
When considering the experimental test results, and the faster ignition of Coal-B, the lower temperatures at the front of the grate are to be expected.

CFD modelling results

The experimental test setup was modelled with CFD, using Coal-B to determine coal specific empirical constants. Figure 8 shows temperature contours of the experimental setup with Coal-B.

Figure 8: Temperature contours of fixed bed reactor [K]



The parameters determined from modelling the fixed bed reactor were then used to model the 100 t/h industrial boiler, with boundary conditions as determined from site measurements.

Temperature and an iso-surface of the flame are depicted by Figure 9 and Figure 10 respectively.

Figure 9: Temperature contours of 100 t/h boiler on Coal-B [K]

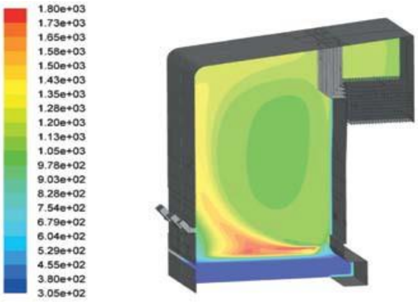


Figure 10: Iso-surface representing a steady state flame in [K]

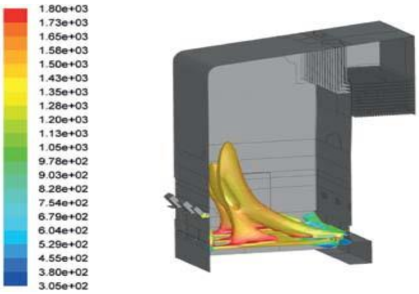


Table 3: Summary of site measurements and CFD prediction at positions 1, 2, 5 and 6 for Coal-B [°C]

Position	CFD	Measurements
1	834	720
2	922	834
5	822	948
6	922	911

From Table 3 it is evident that the CFD prediction is fairly accurate, considering the vast amount of physics required to solve combustion problems.

Conclusions

Temperature measurements on the boiler were carried out at various locations around the boiler with a suction pyrometer. Temperature measurements showed that the temperatures toward the rear of the grate were very similar, with an average of 1 068°C and 1 074°C for Coal-A and Coal-B, respectively. These similar temperatures at the rear of the boiler indicate that the two coals burn at similar temperatures, a property that was confirmed on the fixed bed reactor.

Temperatures on the front of the grate showed more distinctive differences between the coal types. The average temperature on the last part of the grate was 1 129°C and 782°C for Coal-A and Coal-B, respectively. The high temperature on the final part of the grate, as measured on Coal-A, indicates that the combustion was incomplete.

Furnace exit temperatures were similar, with an average of 945°C and 876°C for Coal-A and Coal-B, respectively. From the tests on the vertical down fixed bed reactor, the following observations were made:

- The time to ignition was 60% longer for Coal-A compared to Coal-B;
- Coal-A took 80% longer to reach stable combustion compared to Coal-B;
- The burn down rate, once combustion is stable, is similar for the two coals;
- Coal-A has 36% more ash content than Coal-B; and
- Coal-A showed a slower time to key points in the combustion process due to the low volatile yield.

The fixed bed reactor showed that it can consistently provide quick and accurate parameters to evaluate the suitability of a given coal in a boiler. This makes it a valuable tool to determine whether a change in coal supplier is necessary or not.

Furthermore, the fixed bed reactor showed that coal specific empirical constants can be determined from the experimental procedure. The CFD can then be used to determine the capacity and efficiency from unburned carbonlosses.

Reference: Du Toit, P.& Van der Merwe, S.W. (2014). Computational fluid dynamic combustion modelling of a bagasse boiler, SASRA 2014.