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The impact of particle size and maceral segregation on char formation in a packed bed combustion unit

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HIGHLIGHTS

- The impact of coal particle size reduction was successfully assessed by petrography.
- Maceral distribution of the feed coal fractions varied from the ROM Highveld coal.
- Small size fractions were more reactive than the large size fraction during combustion.
- −53 mm was more reactive than −37.5 mm due to maceral distribution.
- Maceral segregation has a great influence on the char formation and its reactivity.

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ABSTRACT

Highveld parent coal was crushed into three size fractions, namely: 5 mm–75 mm, 5 mm–53 mm, and 5–37.5 mm. The crushed samples were subjected as feed coals to heating in a packed-bed reactor to investigate the influence of particle size reduction on char formation and reactivity. Coal petrography was utilized to assess the maceral and char formation distribution of the feed coal samples and their packed-bed combustion unit's products. The maceral distribution of the feed coal fractions differed from the typical run-of-mine Highveld coal petrographic composition; the smallest size fractions (−53 mm and −37.5 mm) having the highest vitrinite content. Maceral distribution was further divided into total reactive maceral particles, total inert maceral particles, and total inertinite particles. The −53 mm and −37.5 mm feed coal samples had the highest total reactive maceral particle content. Inert char particles dominated in the packed-bed combustion unit samples due to high inertinite maceral group content of the Highveld coals. Unexpectedly, the −53 mm feed coal sample had higher content of total reactive maceral particles and lower content of total inert maceral particles; whereas the −37.5 mm feed coal sample had high content of reactive maceral particles and high content of total inert maceral particles. This variation in maceral group content lead to the −53 mm feed coal sample being more reactive (producing more devolatilized and porous chars and thus reacting faster with reactant gases) than the −37.5 mm feed coal sample. This was due to inert maceral particles restricting the −37.5 mm feed coal sample from fully softening and reacting with reactant gas. This was also this was attributed to variation in volatile propagation of the three particle sizes. This confirms that a feed coal with smaller particle sizes results in different reactivity, char formation, and better heat transfer during combustion than the feed coal with large particle size range. Another important factor that plays a role in combustion is maceral association; it was observed that maceral distribution has a great influence on the char formation and its reactivity more than coal particle size.

1. Introduction

South African energy supply is dominated by coal which represents 65.7% of the primary energy supply followed by crude oil with 21.6%, renewable and waste at 7.6% and gas at 2.8%. Nuclear, hydro and geothermal and solar energy constitute the smallest portion with 1.9%, 0.4% and 0.1% respectively, currently; solar is

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due to expand significantly [1]. Approximately 90% of the South African electricity is produced from coal [2]. It is evident that South Africa will continue to utilize coal for future generations to come.

Burnout properties of coal depend on many factors such as rank, maceral content [3,4], and particle size. In pulverized coals, particle size is an important factor for burnout properties. Yu et al. [5] studied the impact of coal particle size on proximate composition and combustion properties, the coal particle size ranged from 0.05 to 900 μm. Results of this study showed that a reduction in particle size leads to lower fixed carbon and ash content and higher reactivity. Kok et al. [6] conducted a study on the influence of reduction of Cayirhan coal particle size on combustion properties. The Cayirhan coal particle size ranged from −10 + 14 to −400 mesh. This study revealed that a decrease in coal particle size leads to more residue left at the end of the combustion process. Xiumin et al. [7] found that coal particle size has a great influence on coal physical and combustion properties. Specific surface area and pore volume clearly increased with decreasing of pulverised coal particle size. This leads to higher heat and mass transfer which provides a reaction surface during coal combustion. From the above mentioned findings, it is clearly demonstrated that coal particle size has a great influence on coal burning properties.

Physical properties of coal macerals have been extensively described by Stach et al. [8]. Coal grinding has revealed that liberation of coal macerals varies depending on the physical nature of the coal [9–11]. The liptinite maceral group is known to be tough and more resistant to crack formation whereas vitrinite is known to be more brittle during grinding. The fusinite maceral group is more dense and harder than the other coal maceral groups. Semi-fusinite has physical properties which range between those of vitrinite and fusinite maceral groups [12]. Coal particle size reduction can result in a completely different coal maceral distribution between the size fractions. Hower [13] conducted a study on interrelationship of coal grinding properties and coal petrology. In this study it was concluded that the brittle microlithotypes, such as vitrite, partition to the finer fractions. While harder-to-grind microlithotypes such as liptinite- and inertinite-rich bi-and tri-macerals partition to the coarser sizes or, in some cases it varies. Cloke et al. [12], evaluated properties of size fractions from ten world coals and their chars. In this study they observed that unreactive macerals tends to be more segregated with the particle size of the smaller size fraction [12]. Man et al. [14] observed that particle size is necessary to evaluate maceral segregation effects in particle size effect studies since different macerals exhibit different physical and chemical properties and therefore, grinding and sieving operations may lead to selective maceral enrichment in various coal size fractions. Different coal maceral distribution constitutes to different type of char structure, thus different char reactivity [15]. The above statements were proven to be true for pulverized coals. Published research work on the effect of particle size reduction of lump coals during coal processing is very limited. Bunt and Waanders [16] conducted research work on carbon and volatile matter behavior as a function of feed lump coal particle size reduction. Their study concluded that a decrease in particle size resulted in a better heat transfer. At present no research work is published with regard to the influence of lump coal particle size reduction on reactivity performance of coal by coal petrography. This particular paper focuses on char formation of Highveld lump coals with regard to particle size reduction using coal petrography.

2. Experimental method

The Highveld parent coal was crushed into three size fractions namely: 5 mm to 75 mm, 5 mm to 53 mm and 5 to 37.5 mm (referred to as −75 mm, −53 mm, and −37.5 mm) , which were used as feed coal samples. The coal char and ash samples discussed in this paper were produced in a packed bed reactor combustion unit (refer to Bunt et al. [16,17] for further information).

Each feed coal sample was used in a fractional size of −75 mm + 5 mm (hence lump coals as no fine material included). Following combustion, seven equal size samples were collected from the top to the bottom of the packed-bed reactor for each size range tested. The top of the reactor is labelled sample 1, and the bottom of the reactor (the ash bed) is labelled sample 7 (as illustrated in Fig. 1).

2.1. Description of pilot scale packed-bed combustion unit

The packed-bed combustion unit consists of a lined steel jacket with an outside diameter (OD) of 0.8 m and an inside diameter (ID) of 0.4 m, and is 3 m in length [16,17]. The material specification of the refractory lining is high strength, abrasive resistant alumina lining with maximum operating temperature of 1700 °C. The reactor is designed to burn coal particles in an air atmosphere at atmospheric pressure, and reaction temperature is controlled with nitrogen. The combustion unit is equipped with thermocouples for temperature measurements, pressure transmitters for pressure measurements, and rota meters to control the air and nitrogen flow to the reactor.

The required amount of coal was homogenized and loaded using buckets into the pipe reactor to minimize segregation of the packed coal bed. The packed coal bed was heated with a gas burner to get the coal to a temperature where it will burn in an air atmosphere. After an hour, the gas burner was turned off and the air flow was introduced to allow the coal to ignite. Upon reaching a bottom temperature of 600 °C, the air flow was increased to flow until the required temperature of 1250 °C was reached.

The bed temperature was controlled by adjusting the air and nitrogen flow through the bed. The ash bed temperature was controlled at 1250 °C (maximum) and the temperature, pressure and flow to the reactor were logged with a Delta V data logging system. The reactor was left to burn for approximately 18 h before it was cooled down with nitrogen to 25 °C.

After cooling, the reactor was tilted onto its side and opened up like a coffin to allow visual inspection and sample taking of the bed profile (as illustrated in Fig. 1). Seven equal sized fractions were dissected from the entire bed (as illustrated in Fig. 1) and represent the samples that will be discussed in this paper. The ash bed included the material below the flame front in the combustion zone. Table 1 represents the temperature gradients and the reactor zones of the packed-bed combustion unit. Analyses such as proximate analysis and coal petrography were performed on these packed-bed combustion unit samples.

2.2. Chemical and petrographic methods

Proximate analysis was conducted to determine the volatile matter, fixed carbon, and ash in the lump coal samples and reactor generated samples. This analysis was conducted at the Sasol R&D Laboratories, following standard methods [18].

Routine preparation of petrography coal blocks was conducted following ISO 7404/2:1985 [19]. Highveld parent coal was crushed to −1 mm, and block for point counting and image analysis was produced by mounting the coal in resin. The blocks were polished using a Struers TegraForce-1 polishing machine. Maceral group analysis was conducted following ISO 7404/3:1985 [20]. The polished blocks were examined under a Leica DM4500P petrographic microscope at a magnification of 500× with an oil immersion lens, at the University of Witwatersrand.

The petrographically determined carbon form analysis (as reported in Bunt et al. [21]), maceral analysis (as reported in