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# Size Distribution of Nano Particles from Residential Fixed-Bed Coal Combustion

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Particle size distribution (PSD) from domestic coal combustion is an important parameter as it affects air quality, climate modelling, and health. There is limited information in the literature on particle size distribution from residential fixed-bed coal combustion processes. This study aimed to investigate the influence of coal combustion phases (ignition, flaming, and coking) on PSD of fine and ultrafine particles. Fine particle emissions from combustion of D-grade type coal (Ø 40 – 60 mm), in a lab-fabricated coal brazier (imbaula), were monitored using a NanoScan Scanning Mobility Particle Sizer (SMPS). Experiments were carried out using the reduced smoke top-lit updraft method, colloquially known as the Basa njengo Magogo (BnM) method. Particles from the top-lit updraft (TLUD) showed an ultrafine geometric mean diameter centred at approximately 110 nm for the ignition phase, 55 nm for the pyrolysis/ flaming phase, and 33 nm for the transition phase. The particle mode diameter rapidly increased during the ignition phase (145 nm) and gradually decreased during the flaming phase (35 nm) and the transition phase (31 nm).

*Keywords*: Coal combustion, brazier, fixed-bed, nano particles, particle size distribution, health.

## 1. Introduction

Domestic coal combustion in South Africa is an important source of particulate matter (PM) emissions to the atmosphere. Since the 1970s, there has been considerable effort put in characterizing coal combustion products. Submicron aerosols from coal combustion have been found to have stronger impact on human health as they are enriched with toxic elements (Smith *et al*., 2009; Kauppinen & Pakkanen, 1990). Submicron particles have long residences times in the atmosphere, once emitted, and have a higher probability of penetrating deep into the alveolar region of the lungs (Kauppinen & Pakkanen, 1990). In light of this, fine and ultrafine particles from domestic coal combustion are receiving increased attention in South Africa, from both the scientific community and environmental regulators.

Particle size distribution (PSD) from domestic coal combustion processes evolves due to condensation/coagulation within the exhaust/ flue. According to Hosseini *et al*. (2010), particle size distribution can differ as a function of the combustion phase (ignition/flaming/smouldering), fuel characteristics (moisture content, ash content, thermal content) and fuel types (lignite, bituminous, anthracite). Several studies have documented emissions from different coal combustion processes due to the importance of PSD on air quality, health and climate modelling (Zhang *et al*., 2012; Yi *et al*., 2012; Xu *et al*., 2011; Linak *et al*., 2002; Yi *et al*., 2008).

PSD from coal combustion have been studied for a variety of coal combustion processes including in boilers (Linak *et al*., 2002; Kauppinen & Pakkanen, 1990), power stations (Yi *et al*., 2012; Yi *et al*., 2008), and drop tube furnaces (Xu *et al*., 2011). However, earlier studies have shown a wide variation in PSD due to differences in the combustion conditions, as well as measurement techniques and the instruments used (Kauppinen & Pakkanen, 1990). To date, there is limited information in the open and grey literature on PSD from fixed-bed domestic coal combustion devices (Zhang *et al*., 2012). Previous studies on domestic coal combustion in South Africa have focussed on the development of mass and energy specific emission factors (van Niekerk, 1997; CSIR, 2005; Makonese *et al*., 2014). A range of instruments have been employed to measure PSD from coal combustion and these instruments include Scanning Mobility Particle Sizer (SMPS) (Linak *et al*., 2002), Aerodynamic Particle Sizer (APS) (Linak *et al*., 2002), Low-Pressure Impaction (LPI) (Linak *et al*., 2002; Kauppinen & Pakkanen, 1990), Electrical Low Pressure Impactor (ELPI) (Yi *et al*., 2008; Yi *et al*., 2012), Dekati Low Pressure Impactor (DLPI) (Xu *et al*., 2011), and Wide-range Particle Spectrometer (WPS) (Zhang *et al*., 2012).

The objective of this study is to characterize PSD from fixed-bed coal combustion using the top-lit updraft method. A suite of monitoring instruments was employed to measure the evolution of PSD from the ignition phase to the coking phase of combustion. This study reports detailed PSD from domestic coal combustion braziers in use in the Highveld region of South Africa, for the first time.

## 2. Materials and methodology

### 2.1 Combustion lab

Experiments were conducted at the SeTAR Centre stove testing laboratory, situated at the University of Johannesburg, Bunting Road Campus. The combustion experiments were carried out in a galvanised iron hut at the SeTAR laboratory. The flue gases from the burning fuel were exhausted through a 4 m long chimney (located in the centre of the laboratory) with a diameter of 15 cm. A detailed description of the combustion facility including the sampling trains is given in Makonese at al. (2015). Unlike in Hosseini *et al*. (2010), the SeTAR lab was not pressurised with preconditioned ambient air to control parameters such as temperature and humidity. This can only be done if the primary goal is to capture all the entrainment through the ducting system. However, the SeTAR method of determining emission factors/rates is centred on a chemically mass balanced method where only a sample of the exhaust is sufficient.

### 2.2 Particle measurement

The sampling platform was located 4 m from the combustion hut, in a data capturing room where all particles and gas measurements instruments were located. Figure 1 shows a schematic of the measurement and sampling system. First, a sample of the exhaust was drawn from the chimney (~1 m above the burning brazier) and diluted using the SeTAR variable dilutor. Another undiluted sample was channelled to a Testo XL 350 flue gas analyser. The diluted sample was directed to a TSI DustTrak aerosol monitor, a NanoScan Scanning Mobility Particle Sizer (SMPS), and a Testo XL 350 flue gas analyser. In this design, carbon dioxide mixing ratios of the diluted and undiluted exhaust were measured to determine the dilution ratio, using the method described in Makonese (2015). Instantaneous dilution levels across the entire burn sequence were multiplied with the instantaneous particle concentrations to convert the diluted concentrations to equivalent exhaust concentrations.

Particle monitoring instruments are sent for calibration by the manufacturers prescribed intervals, or at least once in a year, and are periodically verified with laboratory standards. Zero and span calibration were performed on all analysers before and after every test run in order to account for small variations in the dilution ratio. For example, the DustTrak and the NanoScan were zeroed with filtered air before each test run.

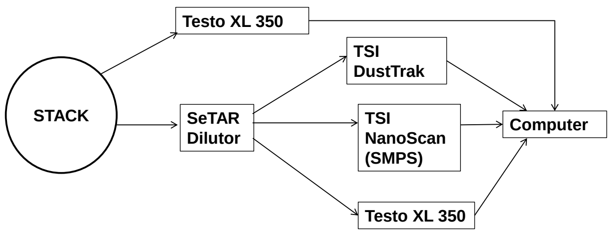


Figure 1: Schematic of the measurement and monitoring system (Adopted and adapted from Hosseini *et al*., 2010)

### 2.3 Fuels and fire preparation

The coal was crushed and sieved to maintain a mean size diameter of 40 mm – 60 mm. Uniform coal sizes were used for each fuel category in our experiments to minimise errors inherent in the use of different coal sizes. Each batch of fuel was analysed for moisture content prior to testing. For the purposes of this study, a D-grade type bituminous coal was used in our experiments in a high ventilation field imbaula using the top-lit updraft method. The fuel specifications, the high ventilation brazier, and the order of laying a top-lit updraft fire are presented in detail elsewhere (see Makonese *et al*., 2014).

## 3. Results and Discussion

### 3.1 Particle Size Distribution (PSD) from 10 nm to 365 nm

Figure 2 shows averaged PSD for the D-grade fuel using the top-lit updraft method as measured by the TSI NanoScan Scanning Mobility particle Sizer. The average size distribution for the entire combustion sequence was found to be bimodal, with minor (lower concentration mode) around 130 nm. After this mode, particle concentration reduces gradually above 180 nm. The geometric mean diameter (GMD) and mode were found to be 51.6 nm and 50.6 nm, respectively. The background PSDs were estimated by averaging size distributions before the ignition phase. Figure 3 shows that background particle concentration decreased sharply above 180 nm. This result is similar to findings by Hosseini *et al* (2010) who noted that background particle concentration decrease sharply above 200 nm.

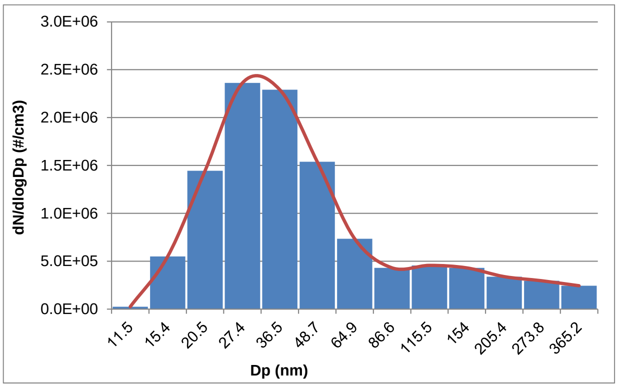


Figure 2: Particle size distributions corresponding to the entire burn sequence

Figure 3 shows background PSD before the burn experiments. As expected, the background concentrations are lower than concentrations measured during the different phases of the burn sequence (Figures 2, 4, 5, 6).

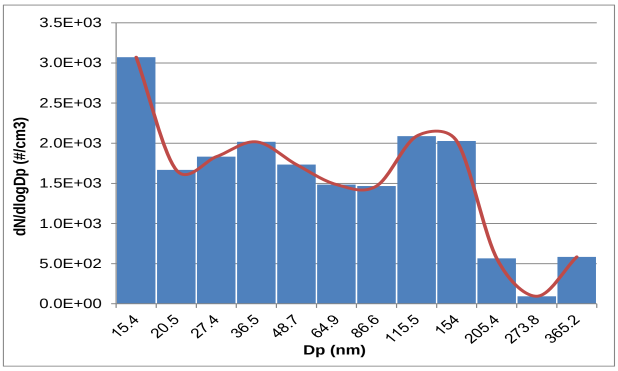


Figure 3: Particle size distributions corresponding to the background concentrations

In this study, an attempt was made to separate combustion phases during each burn sequence, using the criteria developed by Makonese *et al* (2015). Details of this segregation are also described in detail in Makonese (2015). The average size distributions were divided into three combustion phases: ignition; flaming; and coking. The ignition phase shows a bimodal distribution with a GMD of 109.8 nm and a mode that is estimated at 145.3 nm.

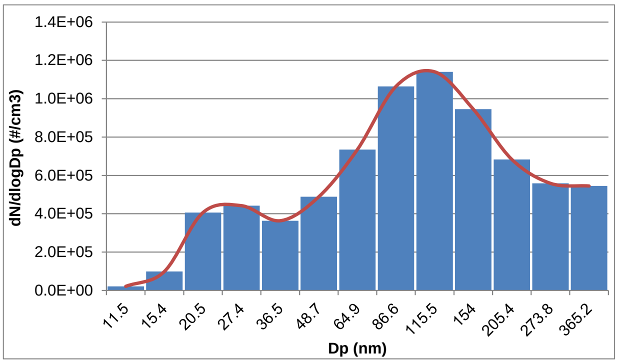


Figure 4: Particle size distribution corresponding to the ignition phase

The bulk of particles emitted during a top-lit updraft coal fire were given off during the flaming stage (Figure 5). The flaming phase shows a bimodal distribution with the GMD estimated at 54.9 nm and the mode at 34.8 nm. The distribution of particles during this combustion phase is similar to that of the average of the entire burn sequence (Figure 2). Hosseini *et al* (2010) reports similar findings when burning biomass under laboratory conditions.

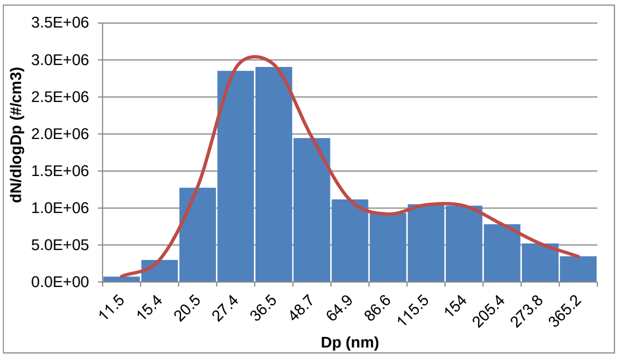


Figure 5: Particle size distribution corresponding to the flaming phase

It was fairly easy to differentiate between the flaming phase and the coking phase during our observations. During the coking phase there were no visible flames and the burning coal had turned red hot. The phase between the flaming phase and the coking phase, referred to as the 'mixed' phase in Hosseini *et al* (2010), was not separately investigated in this study. For the purposes of this study, the flaming and the 'mixed' phases were collectively used under a single umbrella term 'Flaming phase', since the flame is generally visible during the 'mixed' phase.

Size distribution during the coking phase showed a bimodal distribution with a GMD of 32.8 nm and a mode of 31 nm. The size distribution shows that particle concentration gradually increases above 180 nm. However, particle concentration during this phase is comparable to particle concentrations during the flaming phase. A possible explanation for this is that, during the coking phase (at the top of the fuel bed) there will be some coal still igniting and pyrolizing at the bottom of the fuel bed. As the particles pass through the burning red-hot combustion zone, they are burned resulting in the emission of particles with a lower GMD.

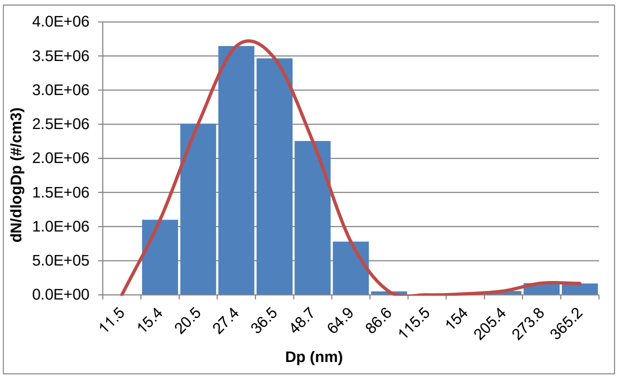


Figure 6: Particle size distribution corresponding to the coking phase

PSD from all combustion phases were found to be bimodal with particle concentrations peaking between 30 and 150 nm. Bond *et al* 2002 observed that when burning coal briquettes particles are emitted in the size range between 20 and 100 nm. Earlier lab-based studies have observed bimodal PSD from pulverised coal combustion with fine particle mode peaks at around 100 nm (McElroy *et al*., 1982).

## 4. Conclusion

This paper presented results of PSD from the combustion of D-grade coal in a high ventilated brazier using the top-lit updraft method. Particle size distributions were measured using a TSI NanoScan Scanning Mobility Particle Sizer. The monitor measured PSD throughout the entire burn sequence (from ignition to coking). The PSD curves were separated into three combustion phases: Ignition, flaming, and coking. The GMD of particle size distribution was estimated to be 51.6 nm for the averaged burn sequence distributions. Particle concentrations were generally high during the flaming and coking phase compared to the ignition phase.

Geometric mean diameter rapidly increased during the ignition phase and gradually decreased during the flaming and the coking phase combustion. Particle size distribution was bimodal across all combustion phases for the D-grade coal used in our experiments.

## 5. Acknowledgments

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