Influence of coal-particle size on emissions using the top-lit updraft ignition method

Lethukuthula Masondo*[1], Daniel Masekameni[1, 2, 3], Tafadzwa Makonese[1, 2], Harold J Annegarn[4], Kenneth Mohapi[1]

[1]Department of Environmental Health: University of Johannesburg
[2]SeTAR Centre, Faculty of Engineering and the Built Environment
[3]Department of Geography, Environmental Management and Energy Studies, Faculty of Science, University of Johannesburg, PO Box 524, Auckland Park 2006, Johannesburg
[4]Energy Institute, Cape Peninsula University of Technology, PO Box 652, Cape Town, 8001

Received: 3 December 2015 - **Reviewed:** 3 February 2016 - **Accepted:** 14 March 2016
http://dx.doi.org/10.17159/2410-972X/2016/v26n1a8

Abstract
Despite the Government's intervention of an intensive electrification program in South Africa, which has resulted in more than 87% of households being connected to the grid, a majority of low-income households still depend on solid fuel (coal and wood) as a primary source of energy, especially on the central Highveld. In informal settlements, combustion of coal is done in inefficient self-fabricated braziers, colloquially known as imbaulas. Emissions from domestic coal combustion result in elevated household and ambient air pollution levels that often exceed national air quality limits. Continued dependence on coal combustion exposes households to copious amounts of health-damaging pollutants. Despite the health significance of coal-burning emissions from informal braziers, there is still a dearth of emissions data from these devices. Consequently, evaluating the emission characteristics of these devices and to determine the resultant emission factors is needed. The effects of ignition methods and ventilation rates on particulate and gaseous emission from coal-burning braziers are reported in literature. However, to date there are no studies carried out to investigate the influence of the size of coal pieces on brazier emission performance. In this paper, we report on controlled combustion experiments carried out to investigate systematically, influences of coal particle size on gaseous and condensed matter (smoke) emissions from informal residential coal combustion braziers. Results presented are averages of three identical burn-cycles of duration three hours or fuel burn-out, whichever was the soonest.

Keywords
coal particle size; brazier; imbaula, emission factor, smoke

Introduction
Energy is an important factor for economic growth, community development and sustenance of life in South Africa (Masekameni et al., 2014). Globally, more than 3 billion people rely on solid fuels combusted in open fires or traditional stoves, for purposes of cooking and space heating (Smith et al., 2012). Emissions from solid fuels account for 4.3 million deaths per year globally (Gordon et al., 2014). These deaths are more common in developing countries with South Africa being no exception (WHO, 2012). It is argued that these deaths can be reduced by use of cleaner burning cook stoves and the introduction of efficient ignition methods that lead to low emissions (Masekameni et al., 2015).

More than half of the South African population still depend on coal and wood for cooking and space heating needs (Kimemia et al., 2011). In the low to medium economic stratum, these fuels are burnt in inefficient stoves and open fires that do not allow for complete combustion, thus impacting on human and environmental health (Kimemia et al., 2011). In the central Highveld of South Africa, a majority of low-income households burn coal and wood in self-fabricated braziers known colloquially as *imbaulas*, which are constructed from discarded steel drums (Kimemia, 2010). The braziers have holes punched around the sides to provide primary air needed for combustion. These devices are used extensively in winter resulting in severe indoor and ambient air pollution (Makonese et al., 2015). The use of poor quality coal in these devices, results in high emissions of gaseous and particulate matter (Makonese et al., 2014a). Coal fuel commonly used in informal settlements of South Africa is the untreated bituminous coal with ash content of up to 40% and with energy content between 15 and 25 MJ/kg (Annegarn & Sithole, 1999; Pemberton-Pigott et al., 2009).

Smith et al (2014) contends that the continued use of coal in poorly ventilated and inefficient stoves leads to increased exposure to health damaging pollutants and the development of respiratory diseases. Bruce et al (2000) found that 1300 lives, amongst children below the age of five are lost each year due to excessive inhalation of particulate matter from domestic coal combustion between the years 1995-2000 in developing countries. Annegarn and Sithole (1999) reported that these stoves lack performance improvements resulting in increased emissions of particulates and gases.

To reduce emissions of noxious gases and particulate matter, existing or new braziers should be optimised. Optimisation of solid fuel burning appliances should consider stove design parameters (i.e. number and distribution of holes above and below the fire grate, the position of the grate in the bucket), fuel characteristics (such as fuel particle size and fuel quality), and operational practices (including ignition methods and fire tending practices) (Makonese, 2015; Masekameni et al., 2014). For example, the top-lit updraft (TLUD) ignition method has been reported to be an effective way of igniting a fire in a coal brazier. A coal fire ignited using the top-lit updraft (TLUD) method produces less visible smoke compared to a fire ignited using the conventional/traditional method. This TLUD ignition method has become a national priority energy intervention programme due to its estimated 80% reduction in ambient particulate air pollution and 20% reduction in coal use at no additional cost (Makonese et al., 2014b).

The effects of ventilation rates (as a function of the size and distribution of holes around the brazier), coal quality, and ignition methods on emissions of gases and particulates from coal burning braziers are reported in literature (Makonese, 2015; Makonese et al., 2014b). However, there are still limited studies carried out to investigate the influence of the size of coal pieces on brazier emission performance.

In light of the above, this study aims to investigate the influence of coal particle size on the emissions performance of coal-burning braziers using the top-lit updraft method. In this paper, three coal particle sizes are evaluated for emission factors of carbon monoxide (CO_{EF}), CO/CO_2 ratio and $PM_{2.5}$ emission factors, using a high ventilation laboratory designed brazier.

Methodology

Fuel Preparation

D-grade coal from Slater mine in Mpumalanga was chosen for our experiments. The fuel is preferred by local coal merchants. Three different coal particle sizes ranges 20 – 40 mm (small), 40 – 60 mm (medium) and 60 – 80 mm (large) were used to investigate emissions performance in a high ventilation rate (i.e. measured as a function of the number and size of air holes on the sides of the brazier) brazier. Large coal nuggets were crushed into small pieces before sieving them through a 20 x 40 mm wire sieve for the 20 – 40 mm size range for small coal size.

For medium size, coal was sieved through a 40 x 60 mm wire mesh, while for large coal size a 60 x 80 mm sieve was used. In order to ensure that the correct sizes were obtained in each category, the technicians checked the dimensions of a sample of already sieved individual coal particles using a ruler. 4 000 g of selected coal fuel were used for each size category.

Coal analysis

The coal was characterized for thermal content, major elemental (proximate) analysis, moisture and ash content by an independent laboratory (Bureau Veritas Inspectorate Laboratories (Pty) Ltd). The fuel samples were analysed on an air-dried basis. Experimental results presented in this paper are based on the proximate and ultimate analysis results for the D-grade coals used in making the fires. Fuel specifications used during the experiments are provided in Table 1.

***Table 1**: Fuel analysis*

Parameter (Air Dried Basis)	Standard Method	Slater Coal D-Grade
Moisture content (%)	ISO 5925	3.5
Volatiles (%)	ISO 562	20.3
Ash (%)	ISO 1171	24.2
Fixed carbon (%)	By difference	52.0
Calorific value (MJ kg^{-1})	ISO 1928	23.4
Calorific value (Kcal kg^{-1})	ISO 1928	5590
Total sulphur (%)	ASTM D4239	0.63
Carbon (%)	ASTM D5373	62. 6
Hydrogen (%)	ASTM D5373	2.72
Nitrogen (%)	ASTM D5373	1.43
Oxygen (%)	By difference	4.96

Choice of fire-ignition methods

The TLUD ignition method was used to investigate the influence of coal particle size on emissions of carbon monoxide and particulate matter, and the CO/CO_2 ratio.

The order of laying a fire during a top-lit ignition fire entailed the following: first, placing the major portion of the coal load on the support grid in the brazier, then paper and wood kindling, with a few lumps of coal added at an appropriate time after the fire has been lit. In our experiments, 3 000 g of coal was added to the bottom of the brazier onto the fuel grate. 36 g of paper and 450 g of kindling were added. After igniting the kindling, ~1 000 g of coal was added to the brazier above the kindling.

Tests were conducted under controlled laboratory conditions, keeping parameters such as ignition method and ventilation rates constant.

Stove characterisation

The brazier used in our experiments is shown in Figure 1. The brazier has a fuel support grate, made of wire although it is common to have some braziers operated without a fire grate. With a fire grate in place the rate of burning is increased. It should be noted that there is no standard brazier, as the devices vary greatly in terms of the number and sizes of the side holes (i.e. affecting ventilation rates), the presence of a grate and its position in the metal drum (Kimemia et al., 2011).

Ventilation rates affect the overall performance of the stove and these rates differ significantly from one device to the other. To evaluate realistically and compare the performance of two or more braziers, ventilation rates need to be specified. Ventilation rates for the experimental brazier used in the study are given in Table 2.

***Figure 1**: Brazier ignited using the TLUD ignition method*

***Table 2**: Stove description*

Brazier type	Height (mm)	Dia. (mm)	Grate height (mm)	Area of holes below grate (cm²)	Area of holes above grate (cm²)
High ventilation	370	290	185 (50%)	248 (61%)	159 (39%)

Test apparatus

The hood method was used for evaluating emissions (Ahuja et al., 1987). The gas samples were analysed using two Testo® flue gas analysers model (Testo® 350XL/454). The sampling configuration for the undiluted flue gases included, in sequence, a stainless steel tube, a filter holder, and a flue gas analyser. For the diluted channel, the sampling configuration included, in sequence, the dilution system, a Teflon tube channel, and a second Testo® flue gas analyser. Traditional coal stoves (*Imbaulas*) emit high levels of particulate emissions; therefore, the dilution system was used to maintain aerosols emissions within the detection limit of the instrument (150 mg/m³). The Testo® measures Carbon dioxide (CO_2), Carbon monoxide (CO), Nitrogen oxides (NO_x), Nitrogen dioxide (NO_2), Hydrogen (H_2), Sulphur (S), Sulphur dioxide (SO_2) and Oxygen (O_2).

Particle mass concentrations and size segregated mass fraction concentrations were monitored using a DustTrak DRX 8533 aerosol monitor. The DustTrak DRX Model 8533 is a laser-based instrument that measures size fractions of the sampled aerosol, from which mass fractions are deduced. The instrument simultaneously measures size segregated mass fraction concentrations (i.e. PM_1, $PM_{2.5}$, PM_4, PM_{10}, and Total Particle Mass - TPM) over a wide concentration range (0.001–150 mg/m³) in real time. Data points were recorded at 10 s intervals.

Testing apparatus

A schematic description of the sampling train is shown in Figure 2. Section A in the schematic show the mixing point, where raw exhaust sample mixes with compressed air. The diluted sample was drawn at point B. A raw exhaust sample was collected at point C.

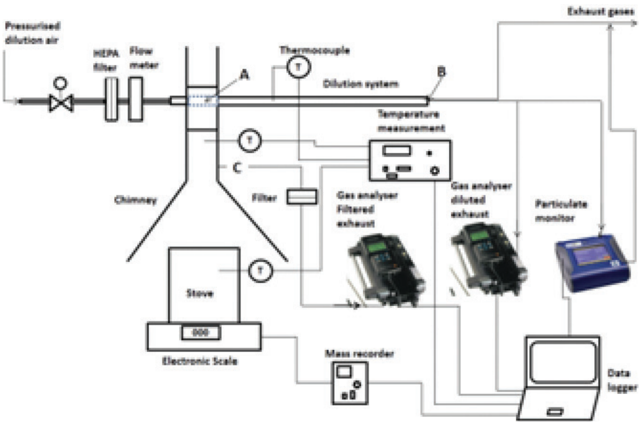

***Figure 2**: Schematic illustration of the experimental dilution set-up for the SeTAR dilution system, showing the mixing point (A) and the sampling diluted exhaust gas point (B) and sampling point (C) is for raw exhaust gases.*

Quality control

For each fuel/stove combination, a series of preliminary burn cycles were carried out to standardise procedures and to minimize the natural variability due to differences in operator behaviour. To familiarise the operators with the testing procedure and with the characteristics of the stove, these trial runs were conducted repeatedly until a stable mode of operation was established. Thereafter three definitive tests were conducted for each fuel/stove combination.

After each fuel/stove combination was tested, the probes were cleaned and the pumps and machines checked and zeroed (Makonese, 2015). Before tests were conducted, the sampling dilution system components were cleaned, assembled, and tested for leaks to prevent contamination from the surrounding air.

A calibration exercise was performed to check the accuracy of the flow rates through each of the critical flow orifices. The sampling dilution system was cleaned prior to testing to minimize pre-existing organic and metal compounds, including the use of high power compressed air and water to remove large particles.

The collection trains, including the stainless steel piping and sampling nozzles, were cleaned with soap, water-rinsed and then air-dried with compressed air. The dilution system was then assembled and connected to the testing rig for a trial run of the tests.

Results

CO emission factors

Carbon monoxide emission factors (CO_{EF}) of the three coal particle sizes results are presented pairwise to compare between coal particle sizes in Table 3). Differences between CO_{EF} pairs are tested for significance using a student T-test, to indicate whether changes in coal particle size result in a significant difference in the emission factor.

A change in coal particle size did not cause a significant difference on the CO_{EF} for the small (20 – 40 mm and medium (40 – 60 mm) particle sizes. However, there is a significant difference in CO_{EF} between medium (40 – 60 mm) and large (60 – 80 mm) coal particles sizes. Results show that there also are significant differences in CO_{EF}, at the 95% confidence level, between small (20 – 40 mm) and large (60 – 80 mm) coal particle sizes. The CO_{EF} for large coal pieces is about three fold higher than for medium and low pieces.

***Table 3**: CO_{EF} of three coal particle sizes in a high ventilation stove using TLUD ignition method*

Coal particle size	Ignition method	CO_{EF} (g/MJ) (n = 3)	Statistical analysis		
			F-Test	P-Value	Sig @ 95%
Medium vs Small	TLUD	1.6 ± 0.09 1.5 ± 0.04	0.31	0.07	No
Large vs Medium	TLUD	4.3 ± 0.22 1.6 ± 0.09	0.31	<0.01	Yes
Large vs Small	TLUD	4.3 ± 0.22 1.5 ± 0.04	0.07	<0.01	Yes

CO/CO_2 ratio over the Burn Cycle

Results of the influence of coal particle sizes on CO/CO_2 ratio are shown in Table 4, for the three different coal particle sizes. There are no significant differences in the CO/CO_2 ratio between small and medium coal particle sizes. However, pairwise comparison between medium and large coal particle sizes indicated a significant difference at the 95% confidence level.

Increasing coal particle size ranges from 20 – 40 mm to 60 – 80 mm, leads to an increase in the CO/CO_2 ratio by ~ 65%. The nominal combustion efficiency is reduced from 97.5% to 92.6%. These results are expected – larger coal particle sizes burn poorly relative to small and medium coal particle sizes.

***Table 4**: Pairwise comparison by coal particle size of average CO/CO_2 ratio over the burn cycle*

Coal particle size	Ignition method	CO/CO_2 ratio [%] (n = 3)	Statistical analysis		
			F-Test	P-Value	Sig @ 95%
Medium vs Small	TLUD	2.5 ± 0.51 2.8 ± 0.22	0.29	0.39	No
Large vs Medium	TLUD	7.4 ± 0.66 2.5 ± 0.51	0.75	<0.01	Yes
Large vs Small	TLUD	7.4 ± 0.66 2.8 ± 0.22	0.19	<0.01	Yes

$PM_{2.5}$ Emission Factors

Results of pairwise comparison of average $PM_{2.5}$ emission factors over the burn cycle of the three coal particle sizes are presented in Table 5. There are no significant differences in $PM_{2.5}$ emission factors between medium and small coal particle sizes. Pairwise comparison between large and medium coal particle sizes resulted in a significant difference in $PM_{2.5}$ emission factors. A similar result is observed between large and small coal particle sizes. Reducing coal particle size ranges from 60–80 mm to 20–40 mm leads to a 50% reduction in $PM_{2.5}$ emission factors.

***Table 5**: Pairwise comparison by coal particle size of average $PM_{2.5EF}$ over the burn cycle*

Coal particle size	Ignition method	Avg. $PM_{2.5}$ (g/MJ) (n = 3)	Statistical analysis		
			F-Test	P-Value	Sig @ 95%
Medium vs Small	TLUD	0.31 ± 0.02 0.42 ± 0.06	0.29	0.39	No
Large vs Medium	TLUD	0.75 ± 0.04 0.31 ± 0.02	0.75	<0.01	Yes
Large vs Small	TLUD	0.75 ± 0.04 0.42 ± 0.06	0.19	<0.01	Yes

$PM_{2.5}$ concentration time series plots over the burn cycle

Time series plots of $PM_{2.5}$ concentrations are shown in Figure 2, for the three coal particle sizes. All three-coal particle sizes experienced high peaks at ignition as the kindling burned and consequently ignited the coal. The $PM_{2.5}$ concentration drops sharply within a few minutes, and then peaks again during pyrolysis phase.

The small and medium coal particle size indicates an earlier ignition of the main fuel bed relative to larger coal size range, indicated by lower $PM_{2.5}$ emissions 30 minutes after ignition (Figure 3). The largest coal size bed (with 80 mm coal particles) takes over 90 minutes to drive off most of the PM and is characterised by an unsteady burn rate. This result is similar to that of Yang et al (2005) who reported that a larger particle-size bed tends to burn more transiently compared to a smaller particle-size bed, which tends to quickly build up to a steady burn pattern. This suggests that the control of a brazier burning larger coal particle sizes needs to be more carefully planned because of the constant variation of the burn pattern as a function of the fuel size (Yang et al., 2005).

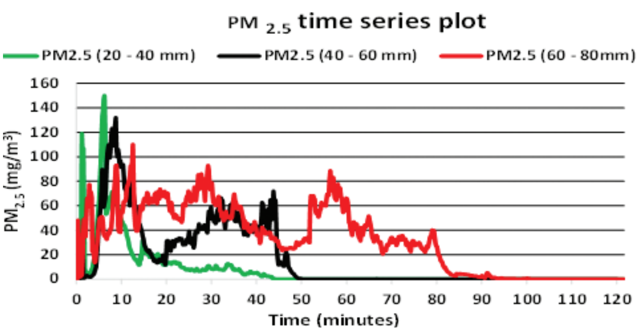

***Figure 3**: $PM_{2.5}$ time series plots for the three coal particle sizes in a high ventilation stove*

In summary, evidence presented shows that coal particle size ranges have an influence on gaseous and particulate emissions from coal braziers. Large coal particle sizes result in poor combustion efficiencies and increased CO and $PM_{2.5}$ emissions. It is recommended that coal particle size ranges of between 20–40 mm be used for optimal brazier performance.

Significance and conclusion

In general, the following conclusions can be drawn from this study. Particulate and CO emission factors increase with an increase in the mean size range of the fuel. Small and medium coal particle sizes produced comparable emissions (CO and $PM_{2.5}$) and CO/CO_2 ratio. The ignition time and the time to reach full pyrolysis are shorter with a bed of smaller particles compared to a bed of larger particles, when the devices are operated under the same conditions. Small coal particle size ranges presented a uniform flame propagation speed for most parts of the combustion process, while large particles showed a less stable transient features where the burning rate, although lower compared to small coal particle sizes, fluctuates throughout the combustion process.

If these results are validated by further testing using stoves with medium and low ventilation rates, as found within the range of artisan manufactured braziers, it would imply that pollution reductions can be achieved by supplying a regulated graded coal size, in the range 20–40 mm, to the domestic coal market. However, small coal particles burn quicker and therefore more of the fuel will be required to complete any given task, leading to an increased financial burden on the user.

Acknowledgements

This work was supported financially by the University of Johannesburg through a URC/Faculty of Science grant to the SeTAR Centre, and in part from a grant from the Global Alliance for Clean Cookstoves (GACC) to the SeTAR Centre as a Regional Stove Testing and Development Centre. The authors thank Gumede K, Gxabuza N, Shabangu M and Maseki J, for their assistance with the combustion experiments.

References

Ahuja, D.R., Veena, J., Smith, K.R., Venkataraman, C. 1987. Thermal performance and emission characteristics of unvented biomass-burning cook-stoves. A proposed standard method for evaluation, *Biomass*, 12, 247-270.

Annegarn, H.J, Sithole, S. 1999. "*Soweto Air Monitoring Project (SAM), Quarterly Report to the Department of Minerals and Energy*", Report No. AER 20.001 Q-SAM, University of Witwatersrand, Johannesburg.

Balmer, M. 2007. Household coal use in an urban township in South Africa, *Journal of Energy in Southern Africa*, 18(3), 27-32.

Bruce, N., Perez-Padilla, R., Albalak, R. 2000. Indoor air pollution in developing countries: A major environmental and public health challenge, *Bulletin of the World Health Organization*, 78, 1078-1092.

Gordon, S. B., Bruce, N. G., Grigg, J. et al., 2014. Respiratory risks from household air pollution in low and middle-income countries, *The Lancet Respiratory Medicine Commission*, 2(10). P 832-860.

Kimemia, D., Annegarn, H., Robinson, J., & Pemberton-Pigott, C. 2011. Optimising the Imbaula stove. *Proceedings of the Domestic Use of Energy (DUE) Conference*, 1 April 2011, Cape Town.

Kimemia, K.D., 2010. Biomass Alternative Urban Energy Economy, The ventilation of Setswetla, Alexandra Township, Gauteng. MSc thesis, University of Johannesburg, Johannesburg.

Makonese, T. 2015. Systematic investigation of smoke emissions from packed bed residential coal combustion devices, PhD Thesis, University of Johannesburg, South Africa.

Makonese, T., Masekameni, D., Annegarn H., & Forbes, P. 2015. Influence of Fuel-Bed temperatures on CO and condensed matter emissions from packed-bed residential coal combustion. *Proceedings of the Domestic Use of Energy (DUE) Conference*, 31 March – 2 April 2015, Cape Town.

Makonese, T., Forbes, P., Mudau, L., & Annegarn, .H. J. 2014a. Aerosol particle morphology of residential coal combustion smoke, *The Clean Air Journal*, 24(2), 24–28.

Makonese, T., Masekameni, D., Annegarn, H., Forbes, P., Robinson, J. & Pemberton-Pigott, C. 2014b. Domestic lump coal combustion: Characterization of performance emissions from selected braziers. *Proceedings of the Twenty-Second Domestic Use of Energy (DUE) Conference*, 30 March–2 April 2014, Cape Town. IEEE Conference Publications, DOI: 10.1109/DUE.2014.6827755, 2014, pp. 1-7.

Masekameni, M.D., Makonese, T., Annegarn H.J. 2014. Optimisation of ventilation and ignition method for reducing emissions from coal-burning imbaulas. *Proceedings of the Twenty-Second Domestic Use of Energy (DUE) Conference*, 30 March–2 April 2014, Cape Town. IEEE Conference Publications, DOI: 10.1109/DUE.2014.6827755, 2014, pp. 1-7.

Masekameni, M.D., Makonese, T., Annegarn H.J. 2015. A Comparison of emissions and thermal efficiency of three improved liquid fuel stoves. *Proceedings of the Twenty-Third Domestic Use of Energy (DUE) Conference*, 31 March–3 April 2015, Cape Town. IEEE Conference Publications, DOI: 10.1109/DUE.2015.7102965, 2015, pp. 71-76.

Pemberton-Pigott, C, Annegarn, H. & Cook, C. 2009. Emissions reductions from domestic coal burning: Practical application of combustion principles. *Proceedings of the Domestic Use of Energy (DUE) Conference*, 2 April 2009, Cape Town.

Smith, K.R., Balakrishnan, K., Butler, C., Chafe, Z., Fairlie, I., & Kinney, P. 2012. Energy and health. In: *Global Energy Assessment: toward a Sustainable Future*, (Johansson T.B., Patwardhan A, Nakicenovic N, Gomez-Echeverri L, eds). New York: Cambridge University Press, 255–324.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z. 2014. Millions dead, how do we know and what does it mean? Methods used in the Comparative Risk Assessment of household air pollution, *Annual Review of Public Health*, 35,185–206.

WHO. 2012. Indoor air pollution: Household indoor air pollution (online). Available from: http://www.who.int/indoorair/en/ [Accessed 15 May 2015].

Yang, B.Y, Ryu, C., Khor, A., Sharifi, V.N., Swithenbank, J. 2005. Fuel size effect onpinewood combustion in a packed bed. *Fuel*, 84: 2026-2038.