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Influence of coal properties on the performance of fixed-bed coal-burning braziers

Tafadzwa Makonese[1], Daniel M. Masekameni[2*], Harold J. Annegarn[1]

[1] *Sustainable Energy Technology and Research Centre, Faculty of Engineering and the Built Environment, University of Johannesburg, P. Bag 524, Auckland Park Bunting Road 2006, Johannesburg, South Africa.*

[2] *Department of Environmental Health, Faculty of Health Sciences, University of Johannesburg, Doornfontein Campus, Cnr Joe Slovo Drive and Beit Street, Doornfontein 2001, Johannesburg, South Africa.*

Abstract

Informal fixed-bed coal-burning braziers are used extensively in low-income communities of South Africa for space-heating and cooking needs. An investigation was carried out on the effects of coal moisture content and coal quality on the thermal and emissions performance of domestic coal-burning braziers in three field-procured braziers (with three different air ventilation rates), using the bottom-lit updraft (BLUD) and top-lit updraft (TLUD) ignition methods. Results showed that an increase in coal moisture content (from 2.4 wt.% to 8.6 wt.%) led to 18% and 30% decreases in fire-power when using the TLUD and BLUD methods, respectively. The combustion efficiency increased by 25% with an increase in moisture content. Measured carbon monoxide (CO) emission factors increased with an increase in moisture content, while carbon dioxide (CO_2) emission factors remained unchanged. The use of A-grade coal resulted in a 49% increase in PM emissions compared with D-grade coal at high ventilation rates, despite no statistically significant differences ($p > 0.05$) in CO and CO_2 emission factors produced between coal grades.

Keywords: *combustion efficiency, emission factors, ignition methods, imbaula, moisture content*

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* *Corresponding author: Tel: +27 11 559 6641;*
email: danielmasekameni@gmail.com

1. Introduction

Coal still plays a major role in the energy mix in South Africa for the majority of low-income households on the Highveld plateau. It is envisaged that these communities will continue to rely on coal to meet their basic energy needs, despite growing concerns over increased electricity tariffs. The fuel is burned in self-fabricated and inefficient metal braziers colloquially known as *imbaulas* (Makonese *et al*., 2014). The stoves can burn wood, coal, or a combination of both, and often rubbish, which can include waste plastic. Small-scale coal combustion stoves and braziers are known to degrade air quality (Mathee, 2004; Scorgie *et al*., 2003; Engelbrecht *et al*., 2002) and are thermally inefficient (Masekameni *et al*., 2014). High prices of alternative fuels and similar corresponding technologies and their unavailability in many parts of the country make rapid transitions and shifts away from traditional fuels and devices unlikely (Bhattacharya *et al*., 2002). Balmer (2007) contended that the low cost of coal fuel makes it attractive for low-income households. Coal combustion in *imbaulas*, like other forms of energy such as electricity, offers dual services to the user – space-heating and cooking. Coal fuel and coal braziers' applications could, therefore, potentially continue to meet the energy needs of the majority of poor households.

The government and the private sector have made concerted efforts to address air quality issues with respect to continued use of coal braziers in the townships (Scorgie, 2012). Realising that rapid electrification does not result in an automatic and complete switch to cleaner fuels (Madubansi & Shackleton, 2006; Davis, 1998), the government encouraged the dissemination and uptake of a domestic coal ignition method known as the *Basa njengo Magogo* (a top-lit updraft method, hereafter referred to as TLUD). In 2003 the then Department of Minerals and Energy piloted the TLUD method in Orange Farm as an alternative to the conventional (bottom-lit updraft, hereafter referred to as BLUD) method of lighting a coal fire in an imbaula (Le Roux et al., 2009). The TLUD method is regarded as a no-cost way of reducing smoke emissions as there are no modifications needed on the combustion device except the manner in which the fire is started (Makonese, 2011; Standish *et al*., 2007; Le Roux *et al*., 2009). The TLUD method is estimated to result in an 80% reduction in ambient particulate air pollution and a 20% reduction in coal use at no additional cost to the households (Le Roux *et al*., 2009; van Niekerk *et al*., 1997).

There is a need to understand how the operation of the stove and fuel properties influence its performance in terms of emissions and thermal performance in addition to improvements in the ignition method. There is, up until now, a lack of information in the open literature on such evaluations in small-scale domestic fixed-bed coal stoves.

This investigation was particularly about the effects of coal moisture content and coal quality on fixed-bed coal braziers. Carbon monoxide (CO), carbon dioxide (CO_2), particulate matter ($PM_{2.5}$ and PM_{10}) were selected as indicator pollutants because of their prominence in health and environmental studies, as well as air quality dispersion modelling (Makonese *et al*., 2017; Shahraiyni & Sodoudi, 2016; Penney *et al*., 2010).

2. Material and method

2.1 Experimental stoves and fuel analysis

Coal is a heterogeneous fuel, and its complex nature makes it difficult to interpret results from laboratory experiments. A more homogenous coal sample would make it easier to identify the effects of coal properties on emissions and thermal performance (Jasinge *et al*., 2011). Three braziers procured from users in communities (referred to hereafter as field stoves) were tested for thermal performance, emissions of gases and particles. Tests were conducted under laboratory conditions at the Sustainable Energy Technology and Research Centre (SeTAR) at the University of Johannesburg. The brazier stoves or *imbaulas* are found in three normal sizes, determined by three commonly available metal drums: 20 L metal paint drums for domestic use; 70-litre metal dustbins or sectioned 200 L oil drums for commercial purposes and typically used in street-side food vendors. Figure 1 shows a photograph and schematic diagram of a high ventilation brazier used in the experiments. Stove ventilation rates were estimated from the number, size, and density of air holes below and above the fire grate. The devices were categorised into high, medium and low ventilation rates, depending on the total air hole area. Quantitative results of ventilation rates and other *imbaulas* used in this study are presented elsewhere (see Makonese *et al*., 2015).

The braziers commonly have a fuel support grate, made of wire or a perforated plate. For example, the high ventilation brazier had a fire grate positioned about 175 mm and 200 mm from the base and the brim of the stove respectively. This fire grate increases the rate of burning. It should be noted that there is no standard *imbaula* as the devices vary widely with respect to the number and size distribution of side holes and the presence of a grate and its position in the metal drum (Kimemia *et al*., 2011).

The coal was purchased from local coal merchants and was compared with coal sourced directly from a colliery (Slater Coal Mine) in Witbank Emalahleni coalfield, South Africa. Two grades of coal fuel were consequently purchased (A-grade and D-grade) for the comparative tests, in quantities of approximately 100 kg. Because coal is a hetero-

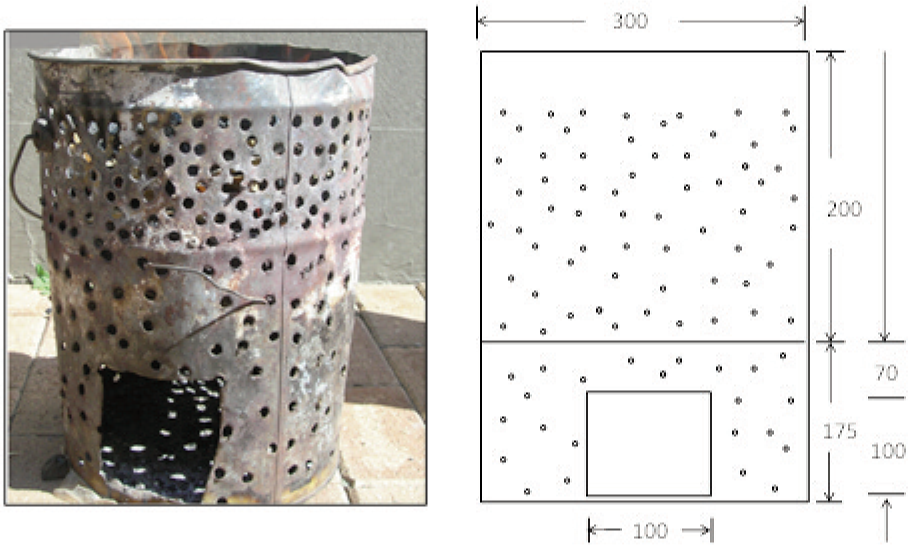

Figure 1. A photograph and schematic representation of a high ventilation field-procured optimised brazier stove used in the experiments (not drawn to scale – dimensions are in mm).

geneous fuel, the coal in each batch was reasonably mixed on the floor with a shovel for homogeneity before 2 kg samples of each sample (with coal pieces in the range 40 mm<D<60 mm) were taken to a commercial laboratory for analyses. The fuels were characterised for calorific value, proximate analysis (moisture, ash, volatile organic compounds, fixed carbon) and ultimate analysis (C, H, S, N, O and mineral elements) given in percentage weight, analysed on an air-dried basis (wt.%, adb). The coal was crushed and sieved to maintain a mean particle size diameter of 40–60 mm. Uniform coal size distribution was used for each fuel category to minimise errors inherent in the use of different coal sizes (Makonese *et al*., 2015). Each batch of fuel was analysed for moisture content before testing.

2.2 Moisture content determination

Each batch of coal was determined for moisture content (MC) before each test. The original A-grade and D-grade coals from Slater Coal Mine were stored in a moisture-free environment for up to 30 days for conditioning prior to analysis. One batch of coal was stored in a container full of water, for the same duration, to increase the coal moisture content. The moist coal was then stored in a moisture-free environment for 48 hrs for the MC to equilibrate, assuming that the 48-hour duration is sufficient for the coal to achieve steady moisture equilibrium before combustion experiments were performed. To determine the moisture content of the coal, a small representative sample (~50 g) was weighed on a calibrated scale with a 0.1 g resolution and then dried in an oven at 100 °C for 24 hours. The sample was then taken out and reweighed. Checking that the coal had attained dry mass, the exercise was repeated every three hours. Steady weight without further decrease confirmed that the coal had reached dry mass. The percentage moisture content was calculated on wet basis using Equation 1.

$$MC_{wet} = (MF_{wet} - MF_{dry} / MF_{wet}) \times 100 \qquad (1)$$

where MF_{wet} is the mass of the wet coal and MF_{dry} is the mass of the dry coal.

2.3 Pot types and sizes

The pots used in this study are aluminium 6 L capacity ccooking vessels manufactured under the brand name Hart, commercially available and widely used for cooking in South Africa and regionally. Water-heating experiments were carried out with 5 L for the large pots with lids, from ambient temperature to the target temperature of 70 °C, to prevent losses through evaporation. It is important to minimise or divert the steam from the combustion flow because it would complicate the analysis of the combustion gases. Excess water vapour has the potential to render the drier on the flue gas analyser less efficient (Makonese, 2011).

2.4 Fire-ignition methods

Experiments involved the TLUD method as the ignition method of choice. In the TLUD, the procedure of laying the fire was as follows: the major portion of the coal load was placed on the fire grate, followed by paper and wood kindling, with a few lumps of coal added at an appropriate time after the fire was lit. A 2 000 g portion of coal was added to the bottom of the brazier onto a fuel grate, followed by 36 g of paper and 360 g of kindling. After ignition of the kindling, 1 000 g of coal was added to the brazier above the kindling (Makonese *et al*., 2014).

2.5 Efficiency calculations

Thermal efficiency (η) of the stoves was determined, which is the ratio of work done by heating and evaporating water to the thermal energy that is generated by burning fuel, as expressed by Equation 2.

$$\eta = (C_p M_w(\Delta T) + M_e L_v) / (M_f(LHV_f) - M_C(LHV_C)) * 100 \quad (2)$$

where

M_w = mass of the water in the pot at the start of the test,

C_p = specific heat capacity of water,

ΔT = rise in the water temperature

M_e = mass of the evaporated water

L_v = latent heat of vaporisation of water

M_f = mass of the raw coal burned

M_C = mass of the remaining char

LHV_f = lower heating value of the coal

LHV_C = lower heating value of the residual charcoal.

Equation 2 does not account for excess ash, which is formed in high ash-containing fuels such as coal and could result in error in the evaluation of thermal performance of fuel/stove combinations (Makonese, 2011). Taylor (2009) contended that short combustion experiments with most woody biomass fuels do not pose a large source of error. When using animal waste and agricultural residues or performing long tests in stoves that are efficient in burning char, accounting for ash could, however, introduce a grave error. The ash may be accounted for by calculating the change in char mass (M_c) as in Equation 3.

$$M_{c_{corrected}} = M_C - (M_f - M_c)A_{c_{fuel}} \quad (3)$$

where

$M_{c_{corrected}}$ = mass of the charcoal corrected,

M_c = mass of the char,

M_f = mass of the raw coal

$A_{c_{fuel}}$ = ash content of the coal on a wet mass basis.

Efficiency can only be determined by separating the coal, char and ash, measuring the proportions of each, and then calculating the energy content of each. Although the method shown in Equation 3 is not recommended as a standard way of determining thermal efficiency, it has the advantage of addressing the influence of ash content in the material removed from a stove at the end of a test, thereby minimising error. There is a deduction for the mass of free ash that should be present in addition to the char. The energy accounting error (due to ash content) can be avoided and is a significant result regarding test metrics since the error may significantly affect most other outputs of the test. As a result, thermal efficiency was calculated using Equation 4.

$$\eta = (C_p M_w(\Delta T) + M_e L_v) / (M_f(LHV_f) - M_{c_{corrected}}(LHV_c)) * 100 \quad (4)$$

The test procedure for determining the power settings used was adopted from Prasad *et al.* (1983), but with minor modifications. The burn rate can be regarded as comparable to fire-power (Bhattacharya *et al.*, 2002). The instantaneous power output of the stove is defined as the mass loss rate multiplied by the lower heating value of the coal, assuming complete combustion (i.e. products of incomplete combustion are minimal) according to Equation 5.

$$P = (LVH * \Delta m) / \Delta t \quad (5)$$

where P is the fire-power of the stove at a specified power setting; Δt is the time interval; Δm is the mass loss in a specified time interval; and LHV is the lower heating value of the coal.

2.6 Gaseous and particle matter emissions

The SeTAR dilution system, which incorporates the hood method, was used to evaluate emissions. As the experimental stoves did not have a flue gas collection system, the stoves were placed under a collection hood attached to the dilution system, which was responsible for the ducting and dilution of the exhaust gas stream. Since a high extraction rate may influence the combustion characteristics of the stove (Bhattacharya *et al.*, 2002), an extractor fan was not used for drawing air through the hood and duct. The hood method could be employed simultaneously with that for the determination of thermal parameters. This has the added advantage of enabling simultaneous measurements of emissions and thermal parameters in a systematic and standard manner (Zhang *et al.*, 1999). Gaseous emissions were monitored using a Testo 350 XL flue gas analyser, while particle emissions were monitored using a DustTrak DRX 8533 aerosol monitor. The schematic of the SeTAR dilution system and experimental setup is presented in detail elsewhere (Makonese *et al.*, 2015; Makonese *et al.*, 2014). Gaseous emissions in parts per million volume can be converted to other units, including energy specific emission factors (EF) in g/MJ, referenced to the energy content of the coal consumed. The net heat gained (H_{NET}), in megajoules (MJ), can be determined easily. This is the heat retained by the pot during a burn sequence. It includes the energy needed to heat the pot and its contents plus the heat of evaporation of water but excludes other heat flows through the pot, specifically radiative and convective losses from the pot sides and top.

The mass of detected gaseous emissions and particulate matter is first multiplied by any dilution factor applied to the equipment, then by the excess air ( ) to obtain the total mass emitted. This approach is based on the foreknowledge that any missing coal was turned into combustion products of some type. This method can track and correctly determine the performance of the stove in real time while burning coal in a heterogeneous manner. For an example, the mass of carbon monoxide and particulate matter (CO and $PM_{2.5}$) emitted during a burn cycle are determined and divided by the net heat gained, yielding energy specific EF in g/MJ as shown in Equations 6 and 7.

$$CO_{EF} = CO(g) \, / \, H_{NET}(MJ) \tag{6}$$

$$PM_{2.5_{EF}} = PM_{2.5}(g) \, / H_{NET}(MJ) \tag{7}$$

3. Results

3.1 Comparative analysis of coal obtained from coal merchants and the colliery

Proximate and ultimate analyses results of the coal used in the experiments, in wt%, adb, are presented in Table 1. Results show that the values for the same coal grade are comparable between the coal obtained from merchants and the colliery, indicating that the coal was representative of the same source. Experiments and experimental results presented herein are based solely on the A-grade, and D-grade coals obtained from the colliery, as over 100 kg of each coal grade was obtained there.

3.2 Influence of coal moisture content on emissions performance

Each batch of coal was determined for moisture content before each test. The moisture content was determined from the batches of coal as received from the field. Two distinct average moisture content values of 2.4 wt% and 8.6 wt.% for two batches of coal were determined using the experiments in Section 2.2. These values were used in the experiments to determine the influence of coal moisture level on the thermal and emissions performance of fixed-bed domestic coal-burning braziers. The emission factors of $PM_{2.5}$, CO, CO_2 and the combustion efficiency, at different coal moisture content, are presented in Table 2. Results show that for both fire ignition methods, measured EF of $PM_{2.5}$ and CO increased with high coal moisture. The differences in emission factors between the moisture content levels were small but significant ($p<0.05$). The correlations were statistically significant, with the correlation coefficients of 0.97–0.99 ($p < 0.05$).

Figure 2 shows the trend of $PM_{2.5}$ emission factors (g/MJ) as a function of different coal moisture content levels across three ventilation rates. Results indicate that, when employing the BLUD ignition technique, there was a marked increase, approximately twofold, in $PM_{2.5}$ emission factors, with increased moisture content levels for all ventilation rates. In contrast, when employing the TLUD ignition technique, there was a slight increase in $PM_{2.5}$ emission factors with increased moisture content, with negligible differences at low ventilation rates.

3.3 Influence of coal moisture content on cooking efficiency and fire-power

The effect of moisture content was investigated on cooking efficiency and fire-power of the stoves with ventilation rates, ignition methods, and coal size held constant. These results are presented in Table 3 and show that, as the MC level increased from 2.4 wt.% to 8.6 wt.%, the cooking efficiency increased, while the fire-power decreased. Fire-power decreased by 18% from 8 kW (at 2.4 wt.% MC) to 6.5 kW (at 8.6 wt.% MC), and the cooking efficien-

Table 1: Proximate and ultimate analysis values for the coals (merchants and colliery) on air-dried basis.

Parameter (air-dried basis)	*Slater coal A-grade*	*Merchant coal A-grade*	*Slater coal D-grade*	*Merchant coal D-grade*	*Method of analysis*
		Proximate analysis results (wt.%, adb)			
Inherent moisture content (%)	3.8	3.6	3.5	3.7	SANS 5925
Volatiles (%)	25.4	26.3	20.3	19.8	ISO 562
Ash (%)	14.0	14.2	24.2	24.8	ISO 1171
Fixed carbon (%)	56.8	55.9	52.0	51.7	By difference
		Ultimate analysis results (wt.%, adb)			
Total sulphur (%)	0.7	0.7	0.6	0.5	ASTM D4239
Carbon (%)	72.4	71.9	62. 6	61.4	ASTM D5373
Hydrogen (%)	3.3	3.1	2.7	3.0	ASTM D5373
Nitrogen (%)	1.6	1.4	1.4	1.5	ASTM D5373
Oxygen (%)	4.4	4.0	5.0	4.6	By difference
Calorific value (MJ kg^{-1})	27.0	26.6	23.4	23.0	ISO 1928

Table 2: Emission factors of stoves for different levels of moisture content of coal.

			$PM_{2.5}$ (g MJ^{-1})		*CO (g MJ^{-1})*		*CO_2 (g MJ^{-1})*		*Combustion efficiency (%)*	
Ignition method	*MC (%)*	*Ventilation rates*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
BLUD	2.4	High	0.6	0.05	4.5	0.3	101	7	4.4	0.4
		Medium	1.1	0.31	5.6	0.4	102	9	5.3	0.4
		Low	1.7	0.20	6.2	0.6	102	4	6.1	0.6
	8.6	High	1.1	0.11	4.5	1.3	103	7	4.5	0.6
		Medium	2.2	0.32	7.4	0.6	104	9	7.2	0.8
		Low	3.0	0.40	9.4	0.3	101	8	9.2	0.5
TLUD	2.4	High	0.2	0.02	4.1	0.3	104	4	4.0	0.6
		Medium	0.6	0.04	4.3	0.3	102	6	4.2	0.4
		Low	0.6	0.02	5.5	0.3	106	5	5.2	0.3
	8.6	High	0.2	0.02	6.2	2.3	101	7	6.1	0.5
		Medium	0.6	0.05	6.5	2.5	103	10	6.3	0.6
		Low	0.7	0.04	7.6	1.1	101	4	7.4	0.4

SD = standard deviation, $PM_{2.5}$ = particulate matter Ø 2.5 μm, CO = carbon monoxide, CO_2 = carbon dioxide, MC = moisture content, BLUD = bottom-lit updraft, TLUD = top-lit updraft.

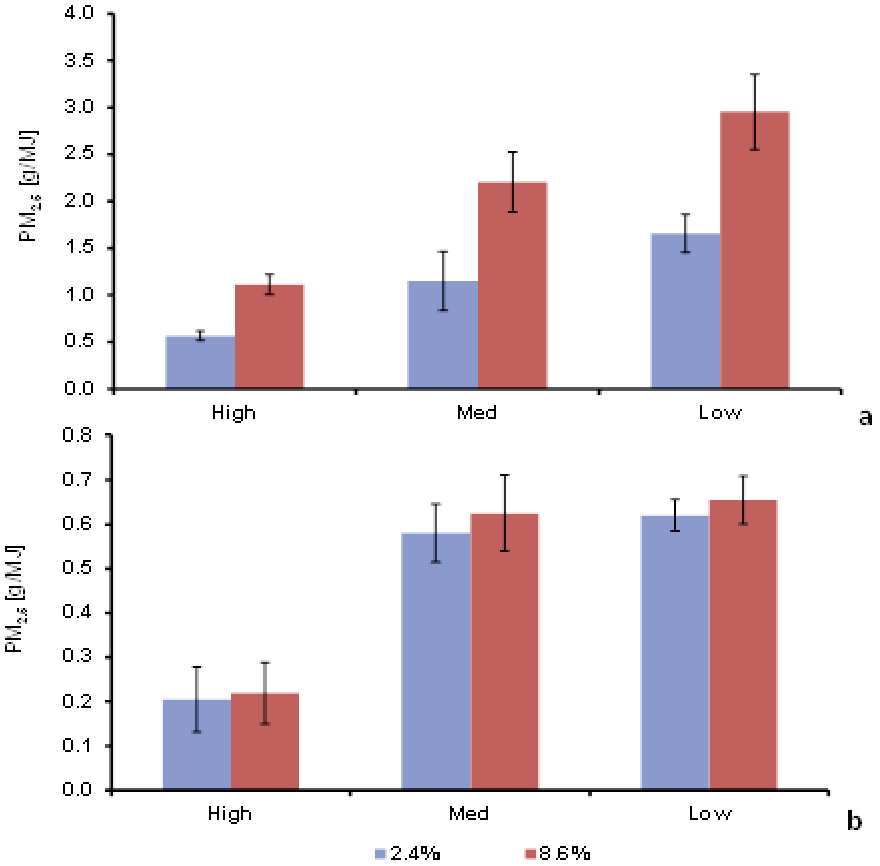

Figure 2: Particulate matter ($PM_{2.5}$) emission factors with different coal moisture content levels across a range of ventilation rates, where (a) = bottom-lit updraft and (b) = top-lit updraft.

cy increased by 24% from 7.8% (at 2.4 wt.% MC) to 10.2% (at 8.6 wt.% MC), when employing the TLUD method in a high ventilation brazier. There was, generally, an average of 18% decrease in fire-power from 2.4 wt.% MC to 8.6 wt.% MC when using the TLUD method for all the ventilations. There was a 30% decrease in fire-power for the BLUD ignition, from 2.4 wt.% MC to 8.6 wt.% MC across the three ventilation rates (high, medium, and low). The cooking efficiency increased by an

Table 3: Comparison between top-lit updraft and bottom-lit updraft fire ignition methods with varying moisture content levels (mean ± standard deviation) N = 3.

		TLUD method				*BLUD method*			
Ventilation rate	*Moisture content*	*Fire-power (kW)*		*Cooking efficiency (%)*		*Fire-power (kW)*		*Cooking efficiency (%)*	
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
High	2.4	7.9	0.8	7.8	0.8	5.9	0.8	4.5	0.3
	8.6	6.5	0.5	10.2	1.4	4.1	0.3	6.0	0.6
Medium	2.4	7.4	0.5	9.6	0.7	5.1	0.2	7.6	0.5
	8.6	6.1	0.6	10.9	1.4	3.8	0.2	10.24	1.4
Low	2.4	6.9	0.4	12.6	1.5	4.4	0.3	8.2	1.3
	8.6	5.7	0.2	12.3	1.6	3.1	0.3	11.0	1.2

Note: TLUD = top-lit updraft, BLUD = bottom-lit updraft, SD = standard deviation

average of 25% across the three ventilations as the moisture content increased from 2.4 wt.% to 8.6 wt.%.

Figure 3 shows that when the moisture content increased fire-power decreased and cooking efficiency increased. This is because stove efficiency tends to decrease as more energy is lost to the surroundings rather than transferred to the pot. The coal in the combustion chamber was burnt gradually from the top–down (for the TLUD method) and from the bottom–up (for the BLUD method), and the existence of water in the coal slowed the combustion and reduced the temperature achieved in the combustion zone. This led to less fuel burned at any given moment, resulting in reduced combustion intensity. This result is consistent with that of McKendry (2002), who reported a reduction in combustion efficiency with an increase in moisture content.

3.4 Influence of coal grade on emissions performance

Effect of coal type on gaseous emissions was investigated, and the results are presented in Table 4. Emissions from a grade D-grade coal were compared with emissions from a grade A-type coal, each with specifications in Section 2.2. Table 4 presents a comparative analysis of gaseous emission

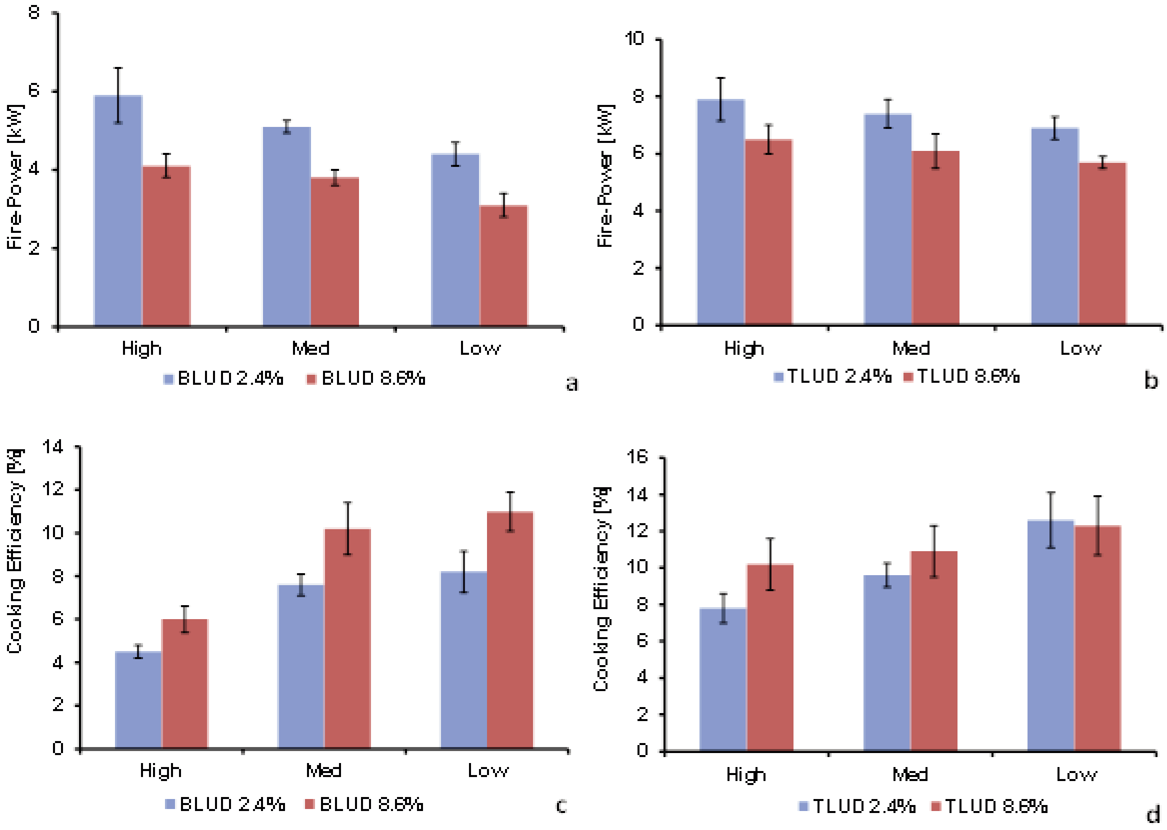

Figure 3: The trend of fire-power and cooking efficiency at different moisture contents across a range of ventilation rates.

Table 4. Comparative analysis of gaseous emission factors between D-grade and A-grade coals, for the BLUD method.

		D-grade coal		*A-grade coal*		*Statistical analysis*			
Pollutant	*Ventilation rates*	*Emission factors (g/MJ)*	*SD (g/MJ)*	*Emission factors*	*SD (g/MJ)*	*% diff. between D-grade & A-grade coal*	*T-stat*	*P-value*	*Sig @ 95% CI*
CO	High	4.1	0.3	4.0	0.2	-1%	0.20	0.85	No
	Medium	4.2	0.4	3.8	0.3	-11%	1.68	0.17	No
	Low	4.6	0.3	5.2	0.2	12%	-2.82	0.05	No
CO_2	High	102	4	98	6	-5%	1.07	0.34	No
	Medium	102	5	99	7	-3%	0.54	0.62	No
	Low	98	6	94	4	-4%	0.87	0.43	No

Note: TLUD = top-lit updraft, BLUD = bottom-lit updraft, SD = standard deviation, CO = carbon monoxide, CO_2 = carbon dioxide, CI = confidence interval.

Table 5. Comparative analysis of gaseous emission factors between D-grade and A-grade coals, for the TLUD method.

		D-grade coal		*A-grade coal*		*Statistical analysis*			
Pollutant	*Ventilation rates*	*Emission factors (g/MJ)*	*SD (g/MJ)*	*Emission factors*	*SD (g/MJ)*	*% diff. between D-grade & A-grade coal*	*T-stat*	*P-value*	*Sig @ 95% CI*
CO	High	4.0	0.2	4.5	0.2	11%	-3.10	0.036	Yes
	Medium	4.1	0.4	4.0	0.1	-1%	0.19	0.862	No
	Low	5.5	0.2	6.1	0.3	10%	-2.95	0.042	Yes
CO_2	High	100	6	97	6	-3%	0.58	0.595	No
	Medium	99	3	97	4	-2%	0.58	0.595	No
	Low	101	5	95	4	-5%	1.34	0.251	No

Note: TLUD = top-lit updraft, BLUD = bottom-lit updraft, SD = standard deviation, CO = carbon monoxide, CO_2 = carbon dioxide, CI = confidence interval.

factors between D-grade and A-grade coal when employing the BLUD method. Results show that there was no statistically significant difference ($p>0.05$) in CO EF produced between coal grades at the medium and high ventilation rates. The use of the A-grade coal resulted in an 11% reduction in CO EF at the medium ventilation rate, while at low ventilation rates CO EF increased by 12%. A statistically significant difference ($p<0.05$) in CO EF between coal grades at low ventilation rates was found when employing the BLUD method. This difference in CO emissions at different ventilation rates could be because of the higher volatile matter content of the A-grade coal, as shown in Table 1.

When comparing the two grades of coal across ventilation rates, results show that there was no statistically significant difference ($p>0.05$) in CO_2 emissions. However, the use of A-grade coal resulted in an average 4% decrease in CO_2 EF across the ventilation rates (Table 4).

Table 5 compares gaseous emission factors between D-grade and A-grade coal when employing the TLUD method. Results show that gaseous pollutant emissions (CO and CO_2) displayed a similar trend to BLUD fires (Table 4). The CO EF were significantly different ($p<0.05$) at high and low ventilation rates but not for the medium ventilation rate. There was, generally, a reduction in CO_2 EF when using A-grade coals compared to D-grade coals. The effect of coal quality (i.e. A-grade and D-grade coal) on PM emissions, when using the BLUD method (Table 6) and when employing the TLUD ignition method (Table 7) was analysed. Results show that for BLUD method there was a statistically significant difference ($p<0.05$) in $PM_{2.5}$ and PM_{10} EF between fuel grades at high ventilation rates. There was, however, no significant difference ($p>0.05$) in $PM_{2.5}$ and PM_{10} EF produced between the D-grade and A-grade coal at low and medium ventilation rates. The use of the A-grade coal resulted in a 49% increase in $PM_{2.5}$ compared with D-grade coal at high ventilation rates (Table 6).

Table 7 shows that, for the TLUD method, the use of A-grade coal resulted in significant increases ($p<0.05$) in PM, 33% at high ventilation rates and 16% at low ventilation rates. At medium ventilation rates, the coal grade change did not give a significant change in PM emissions ($p>0.05$). Zhang *et al.* (2008) reported that coals with low maturity have relatively high volatile contents, which is the precursor material for particulate matter during combustion. Therefore, emission factors of particulate mat-

Table 6. Comparative analysis of particle emission factors between D-grade and A-grade coals, for the BLUD method.

		D-grade coal		*A-grade coal*		*Statistical analysis*			
Pollutant	*Ventilation rates*	*Emission factors (g/MJ)*	*SD (g/MJ)*	*Emission factors*	*SD (g/MJ)*	*% diff. between D-grade & A-grade coal*	*T-stat*	*P-value*	*Sig @ 95% CI*
$PM_{2.5}$	High	1.3	0.1	2.5	0.3	49%	-7.55	0.00	Yes
	Medium	2.9	0.3	3.3	0.2	12%	-2.28	0.08	No
	Low	3.3	0.2	3.6	0.2	8%	-1.75	0.15	No
PM_{10}	High	1.3	0.1	2.5	0.3	49%	-7.54	0.00	Yes
	Medium	2.9	0.2	3.3	0.2	12%	-2.27	0.09	No
	Low	3.3	0.2	3.6	0.2	8%	-1.73	0.16	No

Note: TLUD = top-lit updraft, BLUD = bottom-lit updraft, SD = standard deviation, $PM_{2.5}$ = particulate matter Ø 2.5 μm, PM_{10} = particulate matter Ø 10 μm, CI = confidence interval.

Table 7. Comparative analysis of particle emission factors between D-grade and A-grade coals, for the TLUD method

		D-grade coal		*A-grade coal*		*Statistical analysis*			
Pollutant	*Ventilation rates*	*Emission factors (g/MJ)*	*SD (g/MJ)*	*Emission factors*	*SD (g/MJ)*	*% diff. between D-grade & A-grade coal*	*T-stat*	*P-value*	*Sig @ 95% CI*
$PM_{2.5}$	High	0.24	0.02	0.36	0.02	33%	-7.10	0.00	Yes
	Medium	0.64	0.05	0.69	0.07	8%	-1.10	0.33	No
	Low	0.65	0.06	0.78	0.05	16%	-2.89	0.04	Yes
PM_{10}	High	0.24	0.02	0.36	0.02	33%	-7.13	0.00	Yes
	Medium	0.64	0.05	0.69	0.07	7%	-1.09	0.34	No
	Low	0.65	0.06	0.78	0.05	16%	-2.89	0.04	Yes

Note: TLUD = top-lit updraft, BLUD = bottom-lit updraft, SD = standard deviation, PM2.5 = particulate matter Ø 2.5 μm, PM10 = particulate matter Ø 10 μm, CI = confidence interval.

ter from coal-burning braziers are expected to increase as the volatile matter content of the coal increases.

4. Discussion

The effect of moisture content on gaseous emissions is consistent with findings by Erdöl *et al.* (1999). The increase in CO emission factor appears to be due to lowering of gas phase reaction (oxidation) rates at reduced temperatures caused by higher moisture content (Kumar *et al.*, 2013). A positive correlation between MC in coal and CO emission factor was obtained, which was in contrast to findings in Huangfu *et al.* (2014) and Shen *et al.* (2013). Huangfu *et al.* (2014) and Shen *et al.* (2013) found that CO emission decreased with an increase in MC in the experiments with a TLUD wood stove at four moisture levels. The TLUD stove used in their investigations had secondary air supplied from the top channel ensuring mixing of burned gas with hot secondary air, which resulted in the reduction of CO emission (El May *et al.*, 2013).

The emissions performance of the fuel/stove combination is reduced in situations where the coal is wet. Wet coal is, generally, hard to ignite and often, more starting kindling (wood and paper) is needed to get the fire going. Extra energy is required to vaporise water in the burning of high moisture coal, resulting in reduced coal combustion efficiency and increased emissions caused by incomplete combustion (Shen *et al.*, 2013; Simoneit, 2002; Rogge *et al.*, 1998). Erdöl *et al.* (1999) found that during combustion the surface-adsorbed superficial free water is removed most readily from the coal, while capillary condensed surface moisture and 'absorbed' moisture is more difficult to remove. High coal moisture content lowers the combustion and flame temperatures, leading to increased condensation of volatile matter in the post-flame region of the stove, resulting in elevated levels of PM emissions. The concentration of smoke particles tends to decrease rapidly during the pyrolysis phase of combustion when considering the entire combustion cycle (Mitchell *et al.*, 2016). This is because the water in the coal eventually evaporates and the degree of incomplete combustion is reduced.

An impact on thermal performance is attributed to condensation that normally occurs at the bottom of the pot. When the flame and combustion temperatures are low, the water evaporating from the coal tend to condense on the bottom of the pot, with a possibility to drop into the combustion chamber or coal bed, affecting the performance of the fuel/stove combination. In this study, this phenomenon was not observed.

The stove type and ignition method are the key reason why the relationships between MC and emission factors were in contrast to the results of the study conducted by Huangfu *et al.* (2014). The presence of secondary air holes in the stove plays a major role in minimising emissions of PM and CO. Results from this investigation are in agreement with reported findings of Bhattacharya *et al.* (2002) and Wei *et al.* (2012), where, in both cases, rocket type stoves were used (Jetter & Kariher, 2009), but without secondary air holes. The braziers used in this investigation did not have the ability to inject hot secondary air to the top of the combustion chamber to aid combustion of products of incomplete combustion. For example, when wood logs or firewood chips with higher moisture content are burning in the rocket-type stove, the presence of water in the wood tends to lower the combustion temperatures in the fire hopper, causing thick white smoke to escape out of the stove without being burned. Huangfu *et al.* (2014) used a semi-gasifier cookstove, which was the same type of stove used in Shen *et al.* (2010). In this type of stove, wood is batch loaded and lit from the top. The secondary air-feeding system is responsible for burning the combustion products, including CO and $PM_{2.5}$. Although the presence of water in the coal affects the combustion and flame temperatures, once the wood is lit and char produced on the top, the char would keep the temperatures high enough to combust the coal. This produces combustible products, which burn in the presence of the hot air provided by the secondary air-feeding system (Huangfu *et al.*, 2014).

The significant impact of coal MC on the emission factors observed in this study substantiates the importance of MC in the performance evaluation of fuel/stove combinations. This has implications for future testing protocols that should specify or restrict the MC of the coal to be used in the performance evaluation, to avoid any bias resulting from different MC levels (Huangfu *et al.*, 2014). It can be inferred from the present results that in future studies, especially those aimed at estimating total pollutant amounts based on emission factors, there is need to include the MC of the coal in the different testing regimen and prediction models to minimise the error caused by coal MC levels.

Results of the influence of coal grade on PM emissions are ambiguous, not giving a consistent difference across fire ignition methods or ventilation rates. This aspect requires further investigation, also bearing in mind that coal is a heterogeneous fuel that behaves in a complex manner during combustion. In general, PM emissions are dependent on the volatility of the coal. Coal with high volatile matter is likely to produce high PM emission levels especially if the combustion device is poorly designed. During coal pyrolysis, the coal separates into char and volatile matter. Once the volatiles have been released, they travel up through the combustion chamber of the stove mixing and combusting with primary and secondary air. High volatile coal has the potential to release copious amounts of volatile organic matter upon pyrolysis. If the combustion device is poorly designed or the fire-ignition method not optimised, the volatile matter condenses and is released into the atmosphere as a dense plume of smoke. A-grade coal used in our experiments had high-volatile matter content compared to the D-grade coal (See Table 1). This may explain why an increase in PM was observed with the use of A-grade coal. However, PM formation is a complex process involving many elemental steps, which can be affected by many factors such as the organic content of a fuel, combustion temperature, oxygen supply rate during combustion, and the structure of stoves (Ge *et al.*, 2004).

5. Conclusions

This study investigated the influence of coal properties on the thermal and emissions performance of coal-burning braziers. The following conclusions can be drawn: Coal moisture content has an influence on particles and gaseous emissions. Higher moisture content reduces coal-bed and flame temperatures, resulting in an increase in emissions in the post-flame region of the stove. When considering the entire combustion sequence, the concentration of smoke particles tends to decrease rapidly during the pyrolysis phase of combustion. This is because the water in the coal eventually evaporates and the degree of incomplete combustion is reduced. Low coal moisture content reduces particle emissions by up to 50%. Moist coal produces higher pollution in conventionally ignited braziers. For the TLUD ignition, particle emissions are similar for the two moisture levels for medium and high ventilation rates; for low ventilation, the TLUD emissions for the low moisture coal are relatively small but significant.

Coal quality influences the combustion conditions and the formation of particle and gaseous emissions. The two coal batches used in this study had ash contents of 14 wt.%, adb –A-grade and 24 wt.%, adb –D-grade. Changing from A-grade to D-grade reduces particulate emissions in the top-lit braziers. For the BLUD method, particle emissions are similar with a switch from A-grade to D-grade, except at low ventilation. For the TLUD method, low ash A-grade coal increases particle emissions by up to 100% at any given ventilation rate. Emissions of CO and CO_2 were not influenced by the coal quality.

The significant impact of coal MC and coal quality on the emission factors observed in this study ascertains the importance of MC in the performance evaluation of fuel/stove combinations. This has implications for future testing protocols that should specify or restrict the MC and quality of the coal to be used in the performance evaluation, to avoid any bias resulting from different coal properties.

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