Heterogeneous Stove Testing Methods for the Evaluation of Domestic Solid-Fuel Cookstoves

***Abstract** – More rigorous and detailed test procedures are desirable to determine the effect of various design modifications on the performance of fuel/cookstove combinations, and to optimize their performance. This research paper investigated the effect of a novel heterogeneous testing method to evaluate the performance of domestic solid fuel/cookstove combinations. The water-heating test (WHT) and the 'hood' method were used as the basis of the tests with additional variants of fuel load, power setting and method of ignition. The experimental cookstoves included a typical brazier (Imbaula), a new type Mozambique ceramic cookstove, the baseline Mozambique metal cookstove, and the bottom-lit down-drafting (BLDD) coal cookstove. Results showed that a heterogeneous testing method provides more representative performance data over a wide range of usage scenarios, the equivalent of providing performance curves rather than the minimum and maximum performance points provided by single tasked based methods. This novel heterogeneous testing method generates robust and diagnostic results with which to compare fuel/cookstove technologies. Cookstove designers and programme managers who wish to improve the design of existing and new cookstoves, and to promote efficient fuel/cookstove technologies based on sound laboratory tests can use the principles explored in this study.*

Keywords – Emission factors, heterogeneous testing protocols, natural draft cookstoves, performance curves; solid fuels, thermal efficiency.

1. INTRODUCTION

Currently, about 3 billion people around the globe rely on fuels such as woody biomass, charcoal, coal, agricultural and animal waste for cooking and heating requirements [1]. Heating and cooking with solid fuels, wood and coal, is the norm for millions of poor households in South Africa and neighbouring countries [2]. The rising prices of cleaner, less polluting substitutes and their unavailability in many places prevents a shift away from the use of traditional fuels [3]. Whereas gas and electricity are progressively replacing solid fuels, the latter continue to be used in many low-income households. The burning of solid fuels in poorly designed and fabricated cookstoves leads to copious emissions of pollutants in indoor environments [4], [5] that can adversely affect the health of women and children. Globally, about 4 million premature deaths are recorded annually and are attributable to smoke from biomass cooking [6].

Improving the operation of solid fuel/cookstove combinations has continued over many years, with much effort being placed on fuel efficiency and saving forest resources. Less attention has been given to health consequences as a function of continued solid fuel uses [7]. In recent years, exposure to biomass smoke has been associated with adverse health impacts including diseases of the respiratory system, cardiovascular system, as well as neonatal and cancer outcomes [8]. A recent report has noted significant contributions of domestic biomass burning to climate change [9]. Black carbon (BC) emissions from biomass cooking have received significant attention because of the role of BC in climate forcing and melting of glaciers [10], [11]. Traditional and some 'improved' cookstoves and have the potential to contribute to adverse local and global environmental impacts as well as the increased burden of diseases [10]. There has been substantial interest in different parts of the world to develop and disseminate improved, fuel-efficient and less polluting cookstoves. This has been given an impetus by the emergence of the global alliance for clean cookstoves (GACC).

The literature is awash with information concerning testing methods and protocols used for evaluating fuel/cookstove combinations under controlled laboratory conditions [12], [13]. However, most of the performance evaluation experiments have been largely evaluated using the standardised Water Boiling Tests (WBT) conducted in simulated kitchens [14]. The WBT is a homogeneous single task-based test intended for use at the design phase for quick feedback on design modifications. However, single task-based evaluations of cookstoves have been reported to be flawed because they do not reflect conditions under which the cookstove is used for cooking in practice [14] - [17]. Thus, emission measurements from such tests may not reflect typical domestic emissions during daily activities. Single-task based (homogeneous) evaluations may provide little information to the cookstove designers about the parameters they need to change to improve the performance of the device. Again, the bias inherent in the WBT is thought to cause discrepancies between measured atmospheric pollutant concentrations and modelled emissions [14]. Homogeneous tests do not provide an assessment of the performance of the cookstove under different conditions and therefore may not be useful in making informed decisions about which fuel/cookstove combination to promote.

Other protocols include the Indian and the Chinese stove testing methods. These biomass stove standards are

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based on the premise of boiling water. However, many contain multiple systematic and conceptual errors. Zhang et al. [18] examined a few existing standards and identified systematic and conceptual errors that need to be addressed in the new international standard. The context of use of each fuel/stove combination in different countries was advocated, and this included considering parameters such as convenience, ease of the operation, and appropriateness to local customs [18]. The use of cooking sequences derived from monitoring real-world uses of fuels and stoves were encouraged as these offer the potential to correlate better the laboratory and field performances of fuel/stove combinations. Other errors noted included:

- Re-evaluation of metrics for logical and linguistic consistency.
- Combining the fuel, stove and operator as a single system.
- Revisiting the context of emission performance testing, e.g. when should a combustion sequence end?
- The use of conversion coefficients to convert test results into a standard format. This allows for the inter-comparison of different fuel/stove combinations.
- Bridging the gap between laboratory tests and field tests.
- Bringing experts from developing countries, who are beneficiaries of the international standard to develop such standards [18].

Thus, it can be argued that appropriate testing methods should be representative of cookstove use in practice [16], regarding likely combinations of fuels, their ignition, cookstoves and pots, and range of power settings. In this research, a novel heterogeneous testing method is proposed for the laboratory assessment of cookstoves in a versatile but internally self-consistent manner that can provide a meaningful and representative evaluation of a wide range of fuel/cookstove combinations. The testing method specifically allows for the evaluation of fuel/cookstove combinations according to the manufacturer's instructions, and or as commonly used. However, based on a needs assessment of cookstoves within southern African, the test procedure would require additional variants of selected parameters for evaluation of thermal and emissions performance of the cookstoves. Parameters considered in this study include the ignition method; power settings of the cookstove (high, medium, low) – where feasible and fuel type and load (manufacturer's instructions versus common household use). These factors are chosen as they are often ignored in solid fuel/cookstove performance evaluation experiments. Factors such as fuel moisture content, size of the fuel and pot size, although important to the proposed testing method, are not discussed in this paper but are extensively discussed elsewhere [19], [20].

The robustness of methods and protocols used for evaluating the performance of cookstoves is needed for the generation of accurate, repeatable, and reliable data [12], [21]. This research paper seeks to explore and illustrate how a heterogeneous testing method can provide essential information for the evaluation of cookstove performance. The research also indicates why task-based evaluations are inadequate for the performance assessment of domestic solid-fuel cooking devices. This novel heterogeneous testing method generates robust results with which to compare competing fuel/cookstove technologies. Such comparisons are needed as part of the growing debates surrounding the development and establishment of an international cookstove testing standard. The comparisons are also needed as part of emerging air quality management strategies to improve quality of life in countries that are still dependent on combustion cookstoves for domestic cooking and heating.

2. MATERIALS AND METHODS

2.1 Experimental Cookstoves and Ignition Methods

The solid-fuel cookstoves used in the experiments included a typical brazier, locally known as the Imbaula and used in Townships on the South African Highveld Plateau, a traditional metal charcoal Mozambique cookstove, a recently developed type of ceramic charcoal Mozambique cookstove, and an innovative SeTAR Bottom-lit down-draft (BLDD) cookstove. Batches of grade-D coal and charcoal were supplied, sufficient to conduct a range of comparative experiments. Each fuel batch was analyzed for moisture content shortly before the commencement of each set of experiments. The coal used in the brazier type cookstove and the SeTAR BLDD had a calorific value of 23.4 MJ/kg. The charcoal used in the traditional metal charcoal and the ceramic charcoal Mozambique stoves had a calorific value of 29.8 MJ/kg. The fuel specifications are given in Table 1.

Table 1. Fuel specifications for charcoal and coal used in the experiments.

Parameter (Air dried basis)	Standard Method	Charcoal	Coal (D-grade)
Moisture content (%)	ISO 5925	5.0	3.5
Volatiles (%)	ISO 562	20.7	20.3
Ash (%)	ISO 1171	1.82	24.2
Fixed Carbon	By difference	72.0	52.0
Calorific (MJ/kg)	ISO 1928	29.8	23.4
Total Sulphur (%)	ASTM D4239	0.10	0.61
Carbon (%)	ASTM D5373	71.7	62.6
Hydrogen (%)	ASTM D5373	1.10	2.7
Nitrogen (%)	ASTM D5373	0.10	1.43
Oxygen (%)	By difference	5.5	4.96

2.1.1 The Imbaula Cookstove

Imbaula (brazier type) cookstoves are hand-made from round galvanized metal paint drums with punched holes of varying sizes around the drum. A wire grate or perforated base of the drum across the middle of the container is used to hold the solid fuel. Imbaulas are found in three characteristic sizes, determined by three commonly available metal drums: 20-litre metal paint drums, 70-litre metal dustbins, or sectioned 200-litre oil drums [22]. A typical 20-litre Imbaula is illustrated in Figure 1. Imbaulas commonly have a fuel support grid, made of wire or a perforated plate, but some are operated without a fire grate. With this fire grate in place, the rate of burning is increased. However, there are no standard braziers available in the market as the devices vary greatly regarding the number, position and sizes of the side holes, the presence and position of a grate in the metal drum [19]. The metal drum used in the experiments was 370 mm high and 300 mm wide. These metal drum cookstoves are used widely in the Townships of South Africa for space heating and cooking, especially in winter. The cookstoves can burn wood, coal, or a combination of both, as well as rubbish which include waste plastic.

Fig. 1. A typical South African Highveld brazier/ Imbaula

Two methods of ignition were used to light an Imbaula fire, namely the top-lit up-draft (TLUD) and the bottom-lit up-draft (BLUD). In the TLUD, 4 kg of coal was added into the Imbaula; 35 g of rolled and twisted newspapers were put on top of the coal, and then 800 g of coarse and fine wood was added; 1 kg of coal was added on top of the wood before lighting the fire. The BLUD is the conventional/traditional method of igniting coal in a brazier. The sequence of laying the fire included 35 g of rolled and twisted newspapers, 800 g wood as kindling, and then 5 kg of coal added soon after the kindling was lit and the fire equilibrated.

2.1.2 The Traditional Charcoal Cookstove

The traditional Mozambique metal cookstove is a portable, single pot cookstove made from scrap metal (Figure 2). It is designed for use with charcoal, but it can burn wood or a variety of agricultural residues. The cookstove is equipped with a fixed grate with the lower chamber acting as an ash-collecting zone. The lower chamber can also be used as a combustion chamber when burning woody biomass fuels and agricultural residues. The cookstove is rectangular with a metallic base and four legs. The cookstove illustrated is 390 mm high, 225 mm wide and has a depth of 220 mm. The cookstove has a mass of 3.3 kg. The grate is made up of 15 bars with an average diameter of 8 mm.

Fig. 2. A photograph of the traditional metal Mozambican charcoal stove.

The cookstove could take a maximum of 900 g of ~ 40 mm charcoal nuggets. The testing protocol was adapted in two key areas to reflect common use of this cookstove better. First, performance can be affected by the quantity of charcoal loaded into the cookstove. As such, the tests were conducted with two distinct charcoal loads that reflected either the manufacturer's recommendation (600g, which partially filled the hopper) or common use (the observed practice is to fill the hopper to the upper lip, corresponding to ~900g). Second, as there is no mechanism to control the power output of the cookstove, a single charge of fuel was used, and the fuel was left to burn through a full burn sequence. A hot start test (such as required by the WBT) was not carried out because the cook stove had a lower thermal mass and cooled rapidly between unloading the ash and re-charging the fuel.

2.1.3 The New Type Ceramic Charcoal Cookstove

The recently introduced Mozambique ceramic cookstove is made up of the ceramic body with an outside top diameter of 235 mm, a bottom diameter of 280 mm and a height of 200 mm (Figure 3). The cookstove weighs 4.5 kg. The design features of the cookstove include a conical rim with a pot rest made from iron rods (Figure 3). The inward curving grate has a depth of 65 mm with 12 equally distributed holes. The diameter of the perforations is ~13 mm. The grate diameter is about 210 mm. The cookstove uses charcoal as fuel, and the fuel hopper can take a maximum of 600 g of charcoal.

Fig. 3. A photograph of the ceramic Mozambican charcoal stove

About 20g of wood chips and 5g of rolled up paper were used as kindling. The charcoal was added to the burning kindling. The pot was added as soon as the fire had equilibrated and the bottom charcoal nuggets were red hot. The top-lit method was attempted on this device during the initial experimental runs but required a lot of kindling (70g of wood chips and 20g of paper) to get the fire going. Thus, the experiments were carried out using the bottom-lit method.

2.1.4 The SeTAR BLDD Coal Cookstove

Bottom-lit down-draft (BLDD) devices are promising candidates for meeting at least the basic demand for low emissions. This innovative prototype cookstove is made of cast iron and uses coal as fuel (Figure 4). The cookstove was development at the SeTAR Centre, University of Johannesburg, South Africa [23], [24]. The cookstove was manufactured using mild and stainless steel. The design includes a fuel hopper, which allows primary air to be fed from the top of the hopper. The primary air drafts downwards through a hotbed of coal that has been ignited at the bottom. Preheated secondary air is fed from the sides of the fuel hopper, and it forms a vortex, which allows for pre-mixing of hot air and escaping gases [23]. The pre-mixture of hot gases is channelled through an anodized cooking deck before exiting via a stainless-steel chimney. The hot stainless steel creates a low pressure in the chimney thereby allowing the air to naturally downdraft through the fuel hopper.

Fig. 4. A photograph of the SeTAR BLDD coal prototype stove

2.2 The Heterogeneous Stove Testing Method

The standard water boiling test (WBT) [25] was used as the basis of our testing procedures with additional variants of selected parameters, which included power setting, fuel loading and ignition method. The hot start was not employed during the test as most of the cookstoves evaluated had lower thermal masses, and it proved dangerous to do so.

2.2.1 Test Procedure

The cookstove was set to its maximum possible power setting (according to manufacturer's instruction or as commonly used) and ignited. The cookstove was allowed to warm up until a constant rate of fuel consumption was observed. Instead of bringing the water to a boil or maintain a simmer, the proposed method employed an objective test referred to, by the cookstove group, as the constant temperature rise method (www.cookstove.net). An amount of water (either 2 L or 5 L for the small and large pot, respectively) was heated from ambient temperature to 80°C at the respective power settings. This method has the potential to give a reliable assessment of the thermal parameters of the cookstove, minimizing evaporative losses and errors inherent in trying to maintain water simmering at 3 – 6 °C below boiling. A simmer is difficult to maintain and requires the user to fiddle with the controls or the burning fuel to adjust the fire-power of the cookstove, causing the water temperature to fluctuate and the emissions to spike. This leads to questions about the usefulness of this metric. The test sequence is presented in Figure 5.

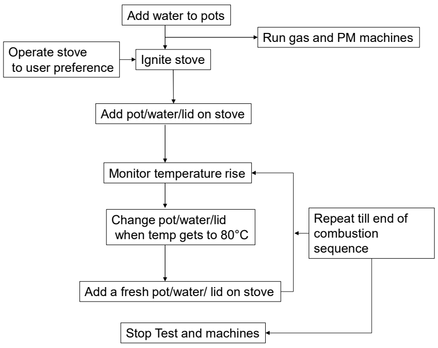

Fig. 5. A schematic of the testing sequence of the HTP

The constant temperature rise method could only be applied to fuel/cookstove combinations designed to be operated across a range of power settings. Most solid fuel cookstoves tested could only be operated at a single power setting, without means of adjustment. For the Imbaulas, a single batch load of fuel was charged at the beginning of the test, and allowed to burn until 90% of the fuel had been used. The fire-power of the cookstove was calculated as an average of fuel consumed over time from ignition to 90% fuel consumption. For purposes of this study, the firepower settings were arbitrarily divided into high, medium, and low. The highest power setting was indicated by > 67% of the highest recorded firepower values, with medium power ranging between 33% and 67% of the highest firepower recorded, while the low power setting below 33% of the highest recorded firepower (Figure 6).

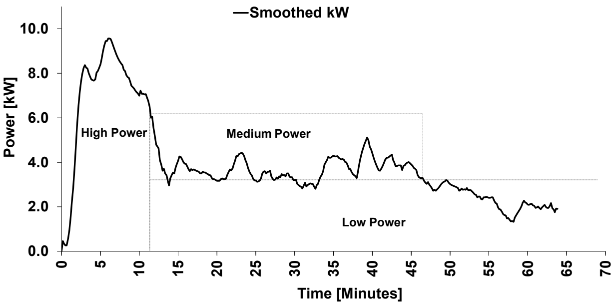

Fig. 6. Profile of firepower against time showing different firepower levels

A digital electricity operated scale with a 32kg range and a 0.001kg resolution supported the entire cookstove, fuel and pot for the small cookstoves. A digital mass balance with a 75kg range and a resolution of 0.01kg was used for the SeTAR BLDD cookstove. Mass readings were recorded automatically every 60 seconds using Adam's scale reader software. Since the mass of the fuel/cookstove/pot combination is known, the loss in mass is attributable to fuel loss as the mas of the fuel/cookstove/pot combination remains constant. The mass balance recorded the mass loss due to the fuel's consumption as a function of time. The instantaneous power output of the cookstove was defined as the fuel mass loss per unit time multiplied by the lower heating value of the fuel, assuming complete combustion. The fuel mass loss and charcoal remaining after every burn sequence were measured for efficiency calculations.

Solid fuel burning in cookstoves is highly heterogeneous as the fuels are not as homogeneous as liquid fuels, leading to great variability in the overall performance of the cookstoves [19]. Wang et al. [10] contended that there is a need to determine the number of test replicates required to minimize standard errors inherent in the experimental design due to differences in cookstove performances. Large sample sizes are needed to minimize the errors. However, due to costs related to a large number of replicates it may not always be possible to meet the requirements of robust statistical analysis [12]. For purposes of this study, five replicates per cookstove were carried out after the users had had enough practice to ignite and operate the cookstoves.

2.2.1 Monitoring of Pollutant Emissions

The hood method [26] was used for evaluating emissions from paraffin, charcoal and coal-burning cookstoves. The hood method can be used simultaneously with the Water Heating Test for the determination of thermal parameters (Figure 7). This method allows the tester to measure pollutant emissions and thermal parameters of the fuel/cookstove combination in a systematic and standard manner [27] simultaneously.

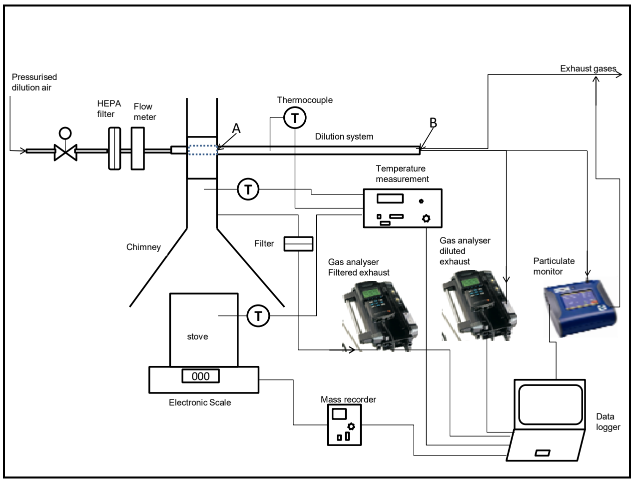

Fig. 7. A diagrammatic representation of the SeTAR cookstove testing set-up, where A is the mixing point in the dilution chamber and B is the sampling point

Two Testo® 350 XL flue gas analyzers were used for monitoring gaseous emissions from the experimental cookstoves. The Testo® measures CO_2, CO, NO_X, H_2, H_2S, SO_2 and O_2. The probe of the first analyzer (measuring filtered undiluted exhaust) was inserted in the chimney for cookstoves with flue (for example, the BLDD coal cookstove) and inside the collection hood for cookstoves without a chimney. The probe of the second analyzer was connected to a variable dilution system (Figure 7). A dilution system was employed that injected compressed air into the drawn flue gases because the particle analyzer had an upper detection limit that was regularly exceeded during testing, especially during ignition. The level of dilution was determined by the measurement of CO_2 levels before and after dilution, achieved using two flue gas analyzers fitted with filters to avoid clogging.

For cookstoves without a flue, the cookstoves were placed under a collection hood, and the gas analyzer probe was inserted in a hood exhaust duct [28]. High extraction rates have been thought to influence the combustion characteristics of a cookstove [29]. As such, extractor fans were not used for drawing air in the experiments. The Testo® analyzers were connected to a computer for real-time data logging and were configured to record the data after every 10 s. At the end of each experimental test run, the data were transferred to a coded Excel® file for processing and analyses.

Particle mass concentration was measured using a calibrated 8533/8534 DustTrak™ DRX particle monitor. This PM monitor is a class 1 laser-based instrument and continually measures particle sizes of the range 0.1–10 µm, with an upper detection limit of 150 mg/m3. During the test, the sampling probe was connected to the dilution system. The monitor was configured to record data every 10 seconds. This corresponded with data also recorded from the flue gas analyzers.

2.3 Quality Control

A series of trial runs were carried to standardize the burn sequence with the intent of minimizing errors due to operator behavior. This was done to acquaint the cookstove operators with the experimental design and operational characteristics of the cookstoves. These trial runs were repeatedly conducted until a stable mode of operation was established. After that, five definitive tests were conducted for each fuel/cookstove combination. After each experimental run, the gas and particle monitor probes were cleaned with pressurized water, and the analyzers were zeroed and checked for faults. Before each test, all fuels were characterized using a bomb calorimeter (CAL2k ECO® calorimeter) for the determination of calorific values. The fuels were also exposed to fuel moisture content tests using a drying oven.

2.3 Performance Indicators

The performance indicators of the cookstoves were derived from calculations and/ modifications of calculations based on the WBT version 3.0.

Thermal efficiency (ŋ) is defined as the ratio of work done by heating a known volume of water to the energy generated from combusting the fuel, and is mathematically represented as:

$$\eta = \frac{C_p M_w (\Delta T)}{M_f (LHV_f) - M_c (LHV_c)} \qquad (1)$$

where M_w is the mass of the water in the pot at the start of the test, C_p is the specific heat capacity of water, ΔT is the rise in the water temperature, M_f is the mass of the raw fuel burned, Mc is the mass of the remaining charcoal, LHV_f is the lower heating value of the fuel, and LHV_c is the lower heating value of the residual charcoal (if any). This calculation assumes that water loss through evaporation is negligible, as the water in the pot is not heated until boiling, but until 80°C after that, the pot is replaced with a fresh pot of water of equal mass.

Equation (1) does not account for excess ash, which is formed in high-ash containing fuels such as coal. Excess ash could result in an erroneous evaluation of thermal performance of fuel/cookstove combinations. Taylor [30] contended that with most woody biomass fuels, and for relatively short tests, the use of Equation (1) would not result in a large source of error. However, when using animal waste and agricultural residues, or with long tests in improved cookstoves, failure to separate ash from char could introduce a huge error in the estimations. In the analysis, ash may be accounted for using Equation 2:

$$M_{c\,corrected} = M_c - (M_f - M_c)AC_{fuel} \tag{2}$$

where $M_{ccorrected}$ is the mass of the charcoal corrected, M_c is the mass of the charcoal, M_f is the mass of raw fuel, and AC_{fuel} is the ash content of the fuel (wbt%).

In this equation, the mass of free ash is deducted from the mass of char measured. The energy accounting error (due to ash content) can be avoided and is an important result since it has the potential to affect other outputs of the test greatly. As a result, thermal efficiency was calculated using the following equation:

$$\eta = \frac{C_p M_w \Delta T}{M_f (LHV_f) - M_{c\,corrected}(LHV_c)} \tag{3}$$

For many enclosed cookstoves, it is impractical to remove unburned fuel, especially in attempting a hot start. It is best to batch load the cookstoves with fuel and operate them in such a way that only char and ash remain at the end of an experiment (or heating phase) or until 90% of the fuel is burned. This is done to obtain a good indication of the energy released from the fuel. The thermal efficiency of cookstoves can then be calculated with reasonable accuracy.

In this study, emission factors were calculated as in Bhattacharya et al. [29] albeit with some adjustments. For example, methane and nonmethane hydrocarbons were included in their estimations. These pollutants were not included in the experiments, and as such, they are not reported herein. It is assumed that CO and CO_2 comprise the bulk of emissions from the experimental combustion processes. Energy-specific emission factors (g/MJ) are reported instead of mass-specific emission factors (g/kg). CO_2 and CO emission factors were estimated as a function of the net heat gained (HNET) from the fuel to the cooking vessel:

$$CO_2EF = \eta CO_2 xMCO_2 (HNET)^{-1} \tag{4}$$

$$COEF = \eta COxMCO \ (HNET)^{-1} \tag{5}$$

where M is the molecular mass of the pollutant.

For PM emissions, emission factors were reported in grams or milligrams of PM emitted per net heat gained [18]. For example, the mass of $PM_{2.5}$ emitted during a burn sequence is determined as follows:

$$PM_{2.5}EF = \frac{PM_{2.5}(g)}{HNET\,(MJ)} \tag{6}$$

3. RESULTS AND DISCUSSION

Results presented in this section are structured to show the importance and need of heterogeneous cookstove testing methods or multiple task-based methods in the evaluation of fuel/cookstove combinations. Although individual fuel/cookstove combinations were evaluated, the goal was not to present a concise comparative assessment of the cookstoves but to highlight the usefulness of heterogeneous stove testing methods over single tasked based methods. Parameters investigated included combustion efficiency as a function of the CO/CO_2 ratio, firepower setting, and fuel loading. The central features of the results will be highlighted, rather than attempting to explain every anomaly in the performance curves. These curves enable us to understand when a result shows deviant behavior, and further systematic testing to understand the causes of variability in the results are required.

3.1 Emissions from the Imbaula

Gaseous and particle mass emissions were measured from coal-burning brazier (Imbaula) employing a top-lit and a bottom-lit ignition method. Figure 8 shows the CO/CO_2 emissions profile from the conventional method of lighting an Imbaula. In each test, 5 kg of coal was used and allowed to burn over an entire sequence (i.e. 90% fuel consumption).

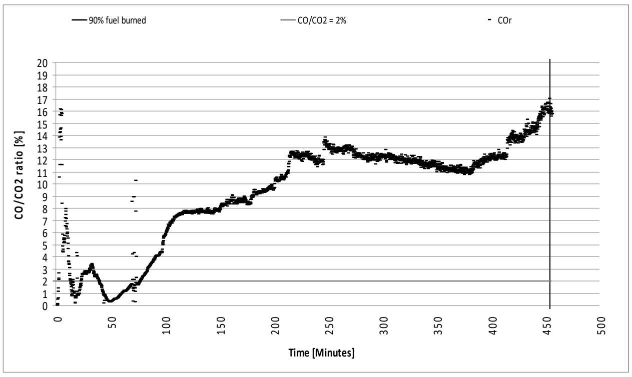

Fig. 8. CO/CO_2 profile for the BLUD Imbaula over an entire burn sequence

Figure 8 shows a profile where the CO/CO_2 ratio spiked during ignition and flame equilibration (i.e. from 0 – 50 minutes). The CO/CO_2 ratio continued to increase from 50 minutes to the end of the test. The BLUD method showed an average CO/CO_2 ratio of 10% throughout the test. The behavior of this CO/CO_2 curve may be explained more readily by reference to the photograph of an Imbaula ignited by the BLUD method (Figure 9).

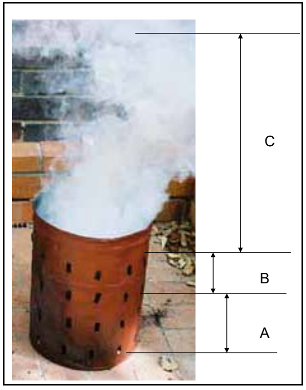

Fig. 9. Photograph showing initial combustion for the BLUD method. (A) Ignition zone (B) fuel zone with the bulk of the coal (C) Flame zone

From Figure 9, Zone A is the initial hot zone where the coal is ignited. At this stage, the coal undergoes thermal decomposition producing tars and semi-volatile compounds (SVOCs) – a process known as devolatilization. The tars released are premixed with air and undergo homogeneous gas-phase combustion, allowing the burning gas mixture to rise, using up available oxygen, and passing through the cooler coal above in Zone B, above the burning Zone A. Coal in Zone B may undergo some pyrolysis depending on whether there is sufficient oxygen plus heat to sustain the combustion. The escaping gases subsequently condensed into droplets and they were emitted into the atmosphere, resulting in visible dense white smoke in Zone C (Figure 9). This poor combustion efficiency was indicated by the CO/CO_2 ratio in the range 9-11% during the pyrolysis phase and an increase in $PM_{2.5}$ (Figure 10). From a health perspective, the cookstove must be kept outdoors at this stage because of the excessive smoke and poor combustion efficiency.

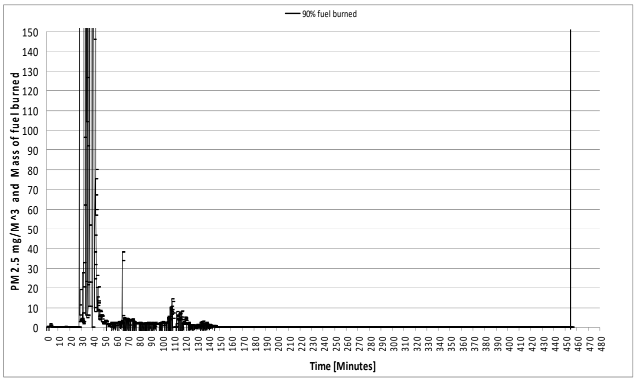

Fig. 10. $PM_{2.5}$ emissions profile for a BLUD Imbaula

During combustion when all the coals had turned red hot, oxygen diffusion and adsorption onto the fuel surface became the limiting factor. This resulted in more CO emissions leading to a reduction in the overall combustion efficiency of the cookstove. In the final stage of burn sequence, there was not enough heat to sustain the combustion of CO to CO_2, and the combustion efficiency dropped significantly [19].

For the TLUD method, the combustion efficiency performance curve has a somewhat different pattern compared to the BLUD. The CO/CO_2 ratio peaks during the initial ignition phase to about 14% before stabilizing for ~ 20 minutes at less than 1% (Figure 11). After 50 minutes from the ignition, the combustion efficiency drops and stabilizes at 5% for about 240 minutes. The CO/CO_2 ratio then rises to 9% from 380 minutes. This is because, at this stage, there was insufficient temperature to burn CO completely increasing the CO emissions.

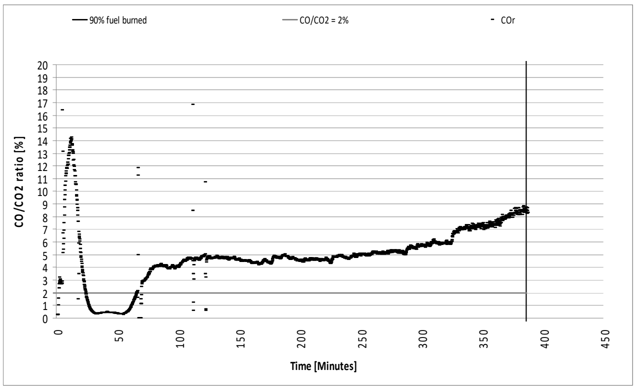

Fig. 11. CO/CO_2 emissions profile from the TLUD method

Looking at the photograph of an Imbaula lit using a TLUD fire (Figure 12); Zone B is the hot zone where kindling and about 1 kg of coal were thermally decomposed. The thermal breakdown of coal resulted in the formation of volatile and semi-volatile matter as discussed above. The TLUD created a downward pyrolytic zone starved of oxygen although the brazier naturally drafts upwards. Zone A (Figure 12), at the bottom of the brazier, contains the bulk of the coal, which produced volatile matter upon heating [19]. The emitted hydrocarbon gases rose through Zone B, which is characterized, by high temperatures and sufficient oxygen. The volatile matter was combusted in this zone resulting in a significant reduction in visible smoke in Zone C (Figure 12). The huge flames that can be seen in Zone C were probably because of an increase in the homogeneous gas phase combustion rate [31]. The moderate combustion efficiency was indicated by the CO/CO_2 in the range 5% (Figure 11). From a carbon monoxide point of view, the cookstove produced sufficient heat for cooking and was safe to take indoors corresponding to ~20 minutes after ignition (Figure 11). It is important to note that the ignition method did not influence the last smouldering phase of combustion, which was marked by an increase in CO.

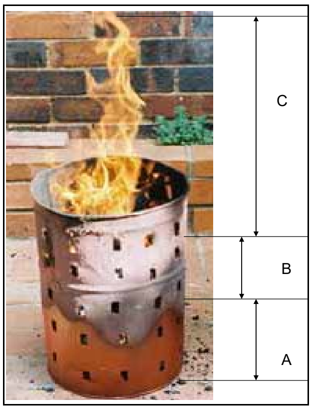

Fig. 12. A photograph showing the initial combustion phases for the TLUD. (A) Fuel Zone with bulk of the coal (B) Ignition zone (C) Flame zone

Comparing the two profiles (Figure 8 and 11), the BLUD ignition method showed a higher average CO/CO_2 ratio during the test than the TLUD ignition method. The average CO/CO_2 for the BLUD was found to be 10% and that for the TLUD method was found to be 5% with the CO/CO_2 ratio remaining stable until the fire began to die down. The TLUD method reached a stage where the cookstove could be taken indoors or used for cooking after ~20 minutes.

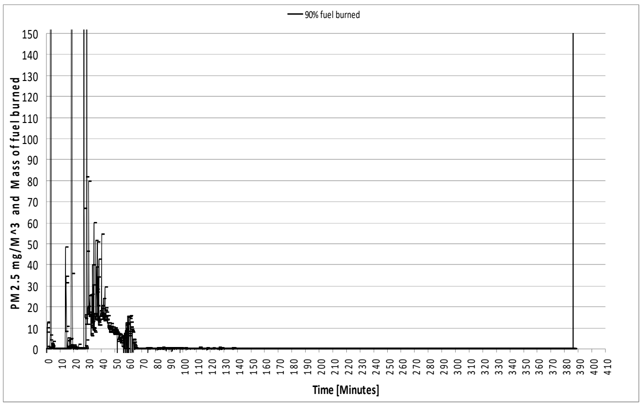

Fig. 13. PM2.5 emissions profile for a TLUD Imbaula

The TLUD showed a lower $PM_{2.5}$ concentration of below 1 mg/m^3 from 65 minutes after ignition (Figure 13) to the end of the test compared to the BLUD, which showed a concentration of below 1 mg/m^3 after 140 minutes (Figure 10). The TLUD gave a $PM_{2.5}$ emissions factor of 888 mg/MJ of fuel burned compared to the BLUD, which gave an emissions factor of 1300 mg/MJ. This showed that the TLUD is a better ignition, regarding both reduced smoke generation (an indication of good combustion) and particle emissions than the BLUD ignition method. This result is comparable to findings in Anderson [32], le Roux [33], and Bhattacharya [29].

The emissions performance curves presented in this section indicate the necessity to conduct replicated tests on the cookstoves, as single tests could yield unrepresentative results with no warning of deviant behavior. The possibility of such variability in the evaluation of cookstoves as received is one of the main characteristics, which heterogeneous testing methods uncover.

3.2 *Emissions from the BLDD Coal Stove*

The cookstove burned 1 kg of coal from ignition to smouldering in ~170 minutes (Figure 14), indicating that it has a lower fuel burn-rate compared to the Imbaula cookstoves. The CO/CO$_2$ ratio for a combustion test of this device is shown in Figure 14. The BLDD coal cookstove showed improved combustion of coal from 20 minutes after ignition to 140 minutes when smouldering begins. The cookstove gave a CO/CO$_2$ ratio of less than 2% for ~120 minutes. After ~ 140 minutes, the CO/CO$_2$ ratio increased to 15% at the end of the test. The useful combustion sequence was thus ~120 minutes.

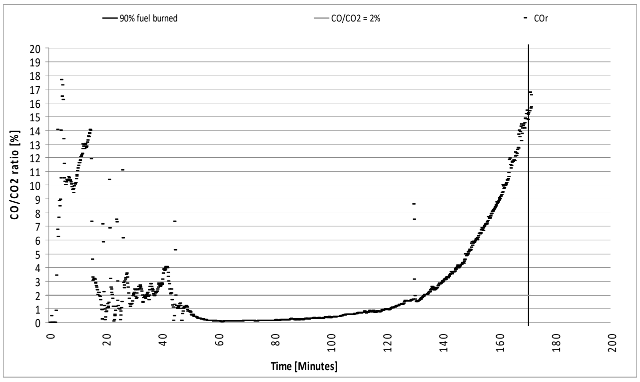

Fig. 14. A graph showing the initial combustion phases for the TLUD. (A) Fuel Zone with bulk of the coal (B) Ignition zone (C) Flame zone

The low CO/CO$_2$ was because of a good air to fuel mix using optimized primary and secondary air during the coking process resulting in combustion that is more complete. All volatiles and combustible gases passed through a bed of red-hot coals, and they were burned. The pre-heated secondary air was naturally drafted into the combustion chamber in a vortex through secondary air slits that are on the sides of the combustion chamber. The downward draft through the coal bed was sustained by a stainless steel designed chimney, which was connected directly to the combustion chamber. The low combustion efficiency during ignition and in the smouldering phase (15% CO/CO$_2$ ratio) (Figure 14), indicated a need for further design considerations to improve the combustion efficiency, as this has the potential to contribute to air pollution. Such performance curves as shown in Figure 13, rather than the maximum and or minimum performance points provided by most stove testing protocols, are important for determining phases of the burn sequence the cookstove needs to be optimized. A protocol, which suggests the use of average figures from an entire burn sequence, may not be able to detect these phases and changes.

3.3 *Effect of Firepower Levels on Emissions*

Table 2 shows CO emission factors in g/MJ of fuel for different fuel/cookstove combinations at multiple power levels.

Table 2. CO emission Factors [g/MJ] against power level for all the experimental stoves.

Cookstove Type	**CO [g] per MJ**			
	Low power	**Medium power**	**High power**	**Whole Test**
Imbaula BLUD	8.3 ± 1.1	4.6 ± 1.2	1.2 ± 0.4	4.7 ± 3.2
Imbaula TLUD	4.3 ± 1.2	3.4 ± 1.7	1.5 ± 0.4	3.1 ± 1.4
Traditional metal cookstove	13.2 ± 2.2	6.4 ± 1.1	4.5 ± 0.8	8.0 ± 4.6
New type ceramic cookstove	2.7 ± 0.4	2.1 ± 0.5	3.3 ± 0.5	2.7 ± 0.6
BLDD coal cookstove	1.4 ± 0.2	0.9 ± 0.1	1.6 ± 0.2	1.3 ± 0.4

The BLDD cookstove has very low emission factors of CO (g/MJ) across a full range of power settings. There is a large variation in the CO emission factor depending on the power setting (Table 2). A standard water boiling test would not reveal this variation if, for instance, only a single power setting was used to evaluate the performance of a fuel/cookstove combination. Thus, for meaningful design feedback (thermal and emissions performance) it is desirable for a fuel/cookstove combination to be tested across its full power range. Evaluating each cookstove across a range of power settings enabled the derivation of performance curves. These are important in assessing thermal parameters and emissions over an entire burn sequence. This is done to improve those parts that produce the most CO$_2$ equivalent and products of incomplete combustion and for identifying design strengths and weaknesses of the cookstoves.

3.3 *Effect of Fueling on Thermal Efficiency of Selected Charcoal Cookstoves*

Early tests conducted with the same 600 g mass of fuel in each cookstove showed that the new type ceramic cookstove had an improved thermal efficiency (32% to 41%) relative to the baseline device (28%) (Figure 15). A laboratory test with 900 g of fuel loaded in the baseline device resulted in a thermal efficiency that was not significantly different ($p>0.05$) to the new ceramic cookstove. This may be due to the reduction in the gap between the base of the pot and the burning fuel, allowing for efficient radiation. However, batch loading the cookstove above its capacity sometimes resulted in quenching of the fire and led to poor thermal and combustion efficiencies. The performance of the baseline device was significantly changed with increasing the fuel load into the cookstove. Thus, for purposes of optimizing the performance of the cookstoves, use of different fuel loads, is encouraged.

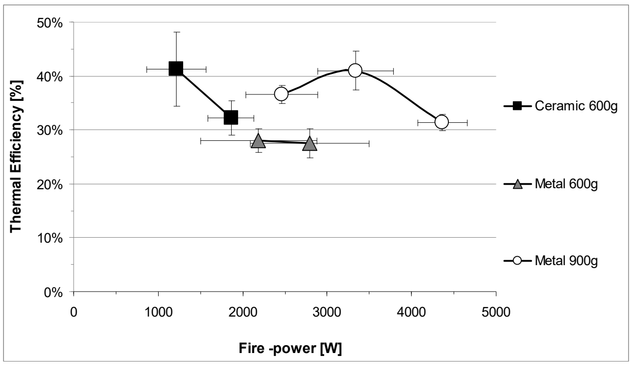

Fig. 15. The relationship between power and thermal efficiency with a traditional Mozambican metal-construction and the new type ceramic Mozambican charcoal stoves

From the discussions presented above, it has been shown that a heterogeneous testing method provides more representative performance data over a wide range of usage scenarios, the equivalent of providing performance curves rather than the minimum and maximum performance points provided by single tasked based methods. The profiles (performance curves) shown in this study are missed if one employs single task-based methods, which do not generate performance curves over a range of power settings and fuel loading. These performance curves are important in that they can reveal design weaknesses and strengths of the device at different power settings across a range of conditions. Under real-life conditions, stoves are not only used operating at the high power setting. Stoves are used for simmering food (medium power), for keeping the food warm (low power), and for space heating (low power). These results are significant for stove design purposes in that they can optimize the efficiency of the stove while using an ignition method and fuel load appropriate to the cookstove across a range of conditions.

4. CONCLUSION

The study dealt with the comparative energetic and emissions analyses of four domestic fuel/cookstove combinations using Heterogeneous stove Testing methods. In general, the thermal efficiency of the baseline Mozambique metal charcoal cookstove increased with an increase in the fuel loaded into the cookstove. However, an increase in fuel load also increased the CO emission factors, corresponding to reduced performance and combustion efficiency. Also, evaluating the performance of a fuel/cookstove combination across the entire burn sequence (which included different power settings) allowed for the derivation of performance curves useful for cookstove design feedback. Emission of CO and $PM_{2.5}$ was significantly less in the case of the TLUD than for the BLUD ignition method. The TLUD ignition method appeared to burn the coal with much less smoke than the BLUD, particularly during start-up.

These results demonstrate the value of comparing performance and emissions using heterogeneous testing methods. Findings have shown that the Heterogeneous stove Testing Protocol is consistent, robust, and transportable; making it a valuable tool for stove design improvements, and for the assessment of stoves under voluntary and compulsory carbon markets. Rigid task-based protocols with standard pots, fuel-loads or fuel specifications, can hide design defects or erroneously rate as inherently poor, a fuel or cookstove technology with good potential. In contrast, rigorous heterogeneous testing methods provide an informative thermal and emissions performance assessment of a fuel/cookstove combination under practical operating conditions. Cookstove designers and programme managers who wish to improve the design of existing and new cookstoves, and to promote efficient fuel/stove technologies based on sound laboratory tests can use the principles explored in this study.

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REFERENCES

[1] Mann J. 2009. The impact on respiratory ailments through reduction of indoor air pollution by smokeless metal stove and solar lighting: Results of a study in rural Nepal. MSc Thesis, Curtin University of Technology.

[2] Ndiema C.K.W., Mpendazoe F.M., Williams A., 1998. Emission of pollutants from biomass stove. *Energy Conversion Management* 39(13): 1357–67.

[3] Ahuja D.R., Joshi V., Smith K.R., Venkataraman C., 1987. Thermal performance and emission characteristics of unvented biomass-burning cookstoves. *Biomass* 12: 247–270.

[4] Barnes D.F., 2006. Clean household energy and indoor air pollution. ESMAP: World Bank, Washington, D.C.

[5] Rehfeuss E., 2006. Fuel for life: Household energy and health. World Health Organization, Geneva.

[6] Gordon, S.B., Bruce, N.G., Grigg, J., Hibberd, P.L., Kurmi, O.P., Lam, K.B., Mortimer, K., Asante, K.P., Balakrishnan, K., Balmes, J., Bar-Zeev, N., Bates, M.N., Breysse, P.N., Buist, S., Chen, Z., Havens, D., Jack, D., Jindal, S., Kan, H., Mehta, S., Moschovis, P., Naeher, L., Patel, A., Perez-Padilla, R., Pope, D., Rylance, J., Semple, S., Martin, W.J., 2014. Respiratory risks from household air pollution in low and middle-income countries. *The Lancet Respiratory Medicine Commission* 2(10): 823–860.

[7] Boy E., Bruce N., Smith K.R., Hernandez R., 2000. Fuel efficiency of an improved wood-burning stove in rural Guatemala: Implications for health, environment and development. *Energy for Sustainable Development* 4: 23–31.

[8] Weinhold B., 2011. Indoor PM pollution and elevated blood pressure: Cardiovascular impact of indoor biomass burning. *Environmental Health Perspectives* 119(10): A442.

[9] World Bank, 2011. Household cookstoves, environment, health and climate change: A new look at an old problem. The World Bank, Washington, D.C.

[10] Wang Y., Sohn M.D., Wang Y., Lask K.M., Kirchstetter T.W., Gadgil A.J., 2014. How many replicate tests are needed to test cookstove performance and emissions? —Three is not always adequate. *Energy for Sustainable Development* 20: 21–9.

[11] Bond T., Doherty S.J., Fahey D.W., Forster P.M., Berntsen T., et al.., 2013. Bounding the role of black carbon in the climate system: a scientific assessment. *Journal of Geophysical Research* 118(11): 5380–5552.

[12] Arora P., Jain S., 2016. A review of chronological development in cookstove assessment methods: Challenges and way forward. *Renewable and Sustainable Energy Reviews* 55: 203–220.

[13] Lombardi F., Riva F., Bonamini G., Barbieri J., Colombo E., 2017. Laboratory protocols for testing of improved cooking stoves (ICS): A review of state-of-the-art and further developments. *Biomass and Bioenergy* 98: 321–335.

[14] Johnson M., Edward R., Frenk C.A, Masera O., 2008. In-field greenhouse gas emission from cook stoves in rural Mexican households. *Atmospheric Environment* 42: 1206–1222.

[15] Zhang Z., Zhang Y., Zhou Y., Ahmad R., Pemberton-Pigott C., Annegarn H.J., Dong R., 2017. Systematic and conceptual errors in standards and protocols for thermal. *Renewable and Sustainable Energy Reviews* 72: 1343–1354

[16] Berrueta V.M., Edwards R.D., Masera O.R., 2008. Energy performance of wood burning cook stoves in Michoacán, Mexico. *Renewable Energy* 32: 859–870.

[17] Roden C.A., Bond T.C., Conway S., Pinel A.B.O., MacCarty N., Still D., 2009. Laboratory and field investigations of particulate and carbon dioxide emissions from traditional and improved cookstoves. *Atmospheric Environment* 43: 1170–1181.

[18] Zhang Z., Zhang Y., Zhou Y., Ahmad R., Pemberton-Pigott C., Annegarn H., Dong R. 2017. Systematic and conceptual errors in standards and protocols for thermal performance of biomass stoves. *Renewable and Sustainable Energy Reviews* 72:1343–1354.

[19] Makonese T., Masekameni D.M., Annegarn H.J., Forbes P.B.C. 2017. Emission factors of domestic coal-burning braziers. *South African Journal of Science* 113(3/4): 1–11.

[20] Makonese T., Pemberton-Pigott C., Robinson J., Kimemia D., Annegarn H.J. 2012. Performance evaluation and emission characterization of three kerosene stoves using a Heterogeneous Stove Testing Protocol (HTP). *Energy for Sustainable Development* 16(3): 344–351

[21] Venkataraman C., Sagar A.D., Habib G., Lam N., Smith K.R., 2010. The Indian national Initiative for advanced biomass cookstoves: the benefits of clean combustion. *Energy for Sustainable Development* 14(2): 63–72.

[22] Kimemia D.K., Annegarn H.J., Makonese T., Molapo V., Robinson J., 2010. Characteristics of domestic biomass combustion technologies used in Setswetla, Alexandra Township, Gauteng. Domestic Use of Energy (DUE) Conference Proceedings, Cape Town, South Africa, 29-31 March; 2010, pp. 167–173.

[23] Momade I., Pemberton-Pigott C., Annegarn H.J., 2014. Modelling of bottom-lit down-draft (BLDD) clean-burning coal stove. Proceedings of the Domestic Use of Energy (DUE) Conference, Cape Peninsula University of Technology, Cape Town, 9 June 2014.

[24] Pemberton-Pigott C, Annegarn HJ, Cook C. Emission reductions from domestic coal burning: Practical application of combustion principles. Proceedings of the Domestic Use of Energy (DUE) Conference, Cape Peninsula University of Technology, Cape Town, 14-16 April 2009, pp. 8

[25] Bailis R., Ogle D., MacCarty N., Still D., Edwards R., Smith K., 2007. The Water boiling Test Version 3.0: Cookstove Emissions and Efficiency in a Controlled laboratory. Household Energy and Health programme, Shell Foundation, United Kingdom.

[26] Ballard-Tremeer G., Jawurek H.H., 1999. The "hood method" of measuring emissions of rural cooking devices. *Biomass and Bioenergy* 16: 341-345.

[27] Zhang J., Smith K.R., Uma R., Ma Y., Kishore V.V.N., Lata K., Khalil M.A.K., Rasmussen R.A., Thorneloe S.T., 1999. Carbon monoxide from cook stoves in developing countries: 1. emission factors. *Chemosphere: Global Change Science* 1: 353–366.

[28] 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. pp. 71-76.

[29] Bhattacharya S.C., Albina D.O., Khaing A.M., 2002. Effects of selected parameters on performance and emission of biomass-fired cookstoves. *Biomass and Bioenergy* 23: 87–3955.

[30] Taylor P.R., 2009. The uses of laboratory testing of biomass cookstoves and the shortcomings of the dominant U.S. protocol. MSc thesis, Iowa State University, Ames, Iowa.

[31] Makonese T., Masekameni D.M., Annegarn H.J., Forbes P.B.C., 2015. Influence of fire-ignition methods and stove ventilation rates on gaseous and particle emissions from residential coal braziers. *Journal of Energy in Southern Africa* 26(4): 16–28.

[32] Anderson P.S., 2011. TLUD stoves in 2011: Within a classification of stoves. ETHOS Conference, 28-30 January 2011, Seattle-Kirkland, WA.

[33] Le Roux L.J., Zunckel M., McCormick S., 2009. Reduction in air pollution using the ‘Basa njengo Magogo’ method and the applicability to low-smoke fuels. *Journal of Energy in Southern Africa* 20(3):3-10.