ABSTRACT

Despite more than 87% households in South Africa being electrified, domestic coal combustion still remain a major source of cooking and heating in low-income households on the Highveld. A majority of low-income households burn coal in informal braziers–imbaulas–constructed from 25 L metal drums with holes punched around the sides. These imbaula stoves are hand manufactured without any standard reference with respect to number, size and location of ventilation holes and position of the fuel grate. These devices tend to have poor combustion efficiencies, leading to high emissions of particulate matter and pollutant gases, affecting both indoor and ambient air. This paper focuses on a range of community designed imbaulas and ignition methods (top and bottom lit), with the aim of evaluating thermal and emissions performance using the SeTAR Centre Heterogeneous Testing Protocol (HTP). Three stoves were evaluated, differing primarily in the total area of the ventilation holes. Results show that the stove with largest area of ventilation holes emits less particulate matter, has improved combustion efficiency - CO:CO₂ ratio (4%) and consumes less fuel compared to two other test stoves with smaller areas of ventilation holes. For all stoves tested, the top-lit ignition method showed an 80% reduction in particle emissions compared to the bottom-lit ignition method. From this work, it can be argued that a balance between primary and secondary air inlets and grate height will improve imbaula performance.

Keywords: imbaula, coal combustion, ventilation holes, emissions, Heterogeneous testing protocol

1. INTRODUCTION

Energy use, community development and socio-economic status are interlinked as inseparable factors of quality of life in developing countries, including South Africa [1]. More than 3 billion people globally rely primarily on solid fuels to meet their basic energy needs [2]. Emissions from solid fuels are responsible for 2.6% of ill-health [3] that results in more than 2.5 million premature mortalities per annum in Africa alone [4]. In South Africa, more than half of the population still burn coal and wood for cooking and space heating [5] resulting in elevated household air pollution levels. These exposures increase the health burden of the poor and bring further cost implications in treating affected groups. South Africa spends R1.2 billion per annum in treating people suffering from respiratory illnesses [6]. The most vulnerable groups are woman and children, as they are exposed to emissions during fire preparation and tending, and cooking. Baines [7] reported that more than 1 400 lives of children under the age of five are lost annually due to poor indoor air quality exposure. These deaths can be reduced by introducing cleaner burning appliances and stove ignition methods.

In South Africa, low-income households burn wood and coal in self-fabricated recycled steel drums with holes distributed around, called imbaulas. Such stoves lack any measures of performance optimization, leading to poor combustion and high emissions of pollutant gases and particles [8]. High emissions are further influenced by poor igniting techniques and poor fuel quality [9]. Many people residing on the central Highveld burn coal in poorly ventilated households which further increases exposure incidences to pollutants.

2. COAL BURNING TECHNOLOGIES

Two distinct methods of laying the fuel and igniting imbaula stoves are used in coal burning townships:

(i) The traditional ignition method (also referred to as the Bottom-lit up-draft) follows the order of putting paper and then wood on the fuel support grate. Just after the wood fire is established, the entire coal load is thrown into the stove. At this stage the fire is starved of primary air and a ‘choking’ process starts. The coal is roasted without a visible flame. At this stage the pyrolytic zone migrates upwards. As the coal is heated, it swells and emits volatile organic compounds. Volatiles and semi-volatile organic compounds escape from the hot pyrolytic zone past a cold zone where the VOCs condense before escaping to the atmosphere, leading to visible white smoke (Figure 1). This loss of organic compounds constitutes loss of energy and pollution of the ambient environment.

(ii) The Basa njengo Magogo (also known as the top-lit up-draft) ignition method of laying a fire in an imbaula is a reverse of the traditional ignition technique. The main load of coal is placed on the fuel support grate at the bottom, followed by paper and wood kindling, and then a few coal lumps are added on the top. The few coal lumps placed on top pyrolyse first and in turn heat the bottom coal slowly. This creates a downward migrating pyrolytic zone. As the main load of coal is roasted, initially by radiation heat transfer, coal undergoes thermal decomposition. The escaping volatile and semi-volatile hydrocarbons rise through the combustion zone with sufficient oxygen present to ensure near complete combustion, thereby minimizing particle and gaseous.

OPTIMISATION OF VENTILATION AND IGNITION METHOD FOR REDUCING EMISSIONS FROM COAL-BURNING IMBAULAS

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emissions. Using this method, there is little visible smoke following ignition (Figure 2).

**Figure 1:** *Imbula* stove ignited using the traditional bottom-up updraft ignition method

**Figure 2:** *Imbula* stove ignited using the *Basa njengo Magogo* top-down updraft ignition method

Whichever method is used, after the coal bed is fully pyrolysed and visible smoke emissions have died down, the *imbula* is taken inside the house for cooking and space heating. The traditional ignition technique is preferred as the quickest and easiest method, due to its historic existence in many townships. Initial surveys leading to this project have indicated that low-income households continue to burn coal in *imbulaus* using the traditional ignition method. As shown in Figure 1, the traditional ignition method is closely linked with visible white to black smoke, which last for more than 40 minutes depending on the stove [10]. The top drum acts as a chimney and is intended to increase draft; it is attached only during the ignition phase but cooking is done without the draft drum.

The use of the *top-lit up-draft* methods of fire ignition, as a means to reduce smoke emissions, has been known for over 150 years and advocated elsewhere in the world (e.g. Scotland). In 2004, the Department of Minerals and Energy introduced a short to medium term strategy to minimize exposure to domestic coal combustion emissions in townships by promoting the *top-lit up-draft* ignition method. To give the campaign a local marketing advantage, the method was labelled “*Basa njengo Magogo*” (literally *make fire like the old lady*). This method is associated with 80% reduction in particulate emissions [9, 10].

This study set out to evaluate the performance of three local community constructed *imbula* type stoves. The three stoves were tested as received to quantify both gaseous and particulate emissions.

3. METHODOLOGY

3.1. STUDY AREA

A field study was conducted prior to laboratory testing of the devices to obtain basic information regarding stove operation procedures, fuel type and fuel load. A minor field study was conducted at *Madela kufa* informal settlement in Tembisa Township. At the time of the study, the area was not connected to the main electricity grid. Coal is the primary energy carrier for cooking in summer, and for cooking and space heating in winter. This area was formed in 1995 by backyards tenants of the former formal Tembisa Township. The area has a population of around 2 500 households. The data were collected in May and June, 2013. Information was gathered from the field using a questionnaire. The development of the questionnaire was guided by information gathered from the literature review and a pilot survey which was conducted prior the commencement of the major survey. The literature review and pilot survey was used to inform the study. The questionnaire was structured with both closed and open ended questions. Through the questionnaire useful information was obtained which serves as a basis for laboratory tests.

The *imbula* characterization information was obtained from *Madela kufa* informal settlement. Fifty two households were sampled; thirty nine households were found to burn coal using *imbulaus* for space heating and cooking, while eight households burned coal for the same functions using locally made cast iron stoves. Three households indicated that they do not burn coal. The other observation from the field study indicated fuel stacking with households agreeing to be using a wide suit of fuels which include coal, wood, candle, paraffin and gas to meet their energy needs. All coal burning households were found to be using the traditional ignition method.

3.2. STOVE TESTING

Three stoves retrieved from actual use in the study area were tested for thermal performance, emissions of gases and particles. Tests were conducted under laboratory conditions at the SeTAR Centre situated at the University of Johannesburg. During testing the two common ignition methods were employed namely: the Traditional ignition method (BLUD) and the *Basa njengo Magogo* (TLUD) ignition methods. The test entailed operating the stove as outlined in the SeTAR Heterogeneous Testing Protocol [10]. Specific parameters such as grid height levels, number of holes, sizes of holes, holes patterns and distributions were considered and recorded for each device (Table 1). Proximate analysis and ultimate analysis elements of coal species were done by an external laboratory.

As highlighted by Zhang 2000 “it is appropriate to discuss ‘fuel/stove combination’ as an elementary unit as emission factors are normally expected to be dependent
“on both fuel types and stove types.” In total, three fuel/stove combinations were tested, each with two ignition methods. The coal used in the tests was bituminous coal obtained from Slater Coal mine in Witbank.

3.3. STOVE DESCRIPTION

A set of three stoves was selected from a set assembled by purchasing in-use stoves from users. The stoves were selected to represent the widest range of number of ventilation holes. Characteristics of the three imbaulas are given in Table 1 and are shown in Figure 3.

Table 1: Stove characteristics

<table>
<thead>
<tr>
<th>Stove type</th>
<th>Height (mm)</th>
<th>Dia. (mm)</th>
<th>Grate height (mm)</th>
<th>No. of holes below grate</th>
<th>No. of holes above grate</th>
<th>Total no. of holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imb01 High case</td>
<td>370</td>
<td>290</td>
<td>200</td>
<td>248</td>
<td>159</td>
<td>407</td>
</tr>
<tr>
<td>Imb02 Medium case</td>
<td>370</td>
<td>290</td>
<td>230</td>
<td>189</td>
<td>166</td>
<td>355</td>
</tr>
<tr>
<td>Low case</td>
<td>440</td>
<td>290</td>
<td>250</td>
<td>145</td>
<td>103</td>
<td>248</td>
</tr>
</tbody>
</table>

Figure 3: Images of imbaulas Imb01, Imb02 and Imb03

3.4. FUEL CHARACTERIZATION

Information obtained during field research informed the study which regards to the fuel type and grade. According to the field information, all households burn D-grade, quality coal. In this study D-grade coal was used for the experiments. Pine wood kindling was used to ignite the coal. Properties of the fuels are presented in Table 2.

Table 2: Fuel description

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Moisture content (%)</th>
<th>Calorific value (MJ/kg)</th>
<th>Grade or type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>10</td>
<td>15.3</td>
<td>D-grade</td>
</tr>
<tr>
<td>Wood</td>
<td>8.2</td>
<td>21.3</td>
<td>Pine wood</td>
</tr>
</tbody>
</table>

3.5. TESTING APPARATUS

The entire stove and components were placed on top of a digital weighing scale under the gas collecting hood. The mass of paper (35 g), wood (400 g) and coal (4 000 g) was used at each sets of test Two gas analysers Testo XL 350 were used to measure the gas concentrations (O₂, CO₂, CO, SO₂, and NOₓ). A DustTrak™ 8350 monitor was used to measure particulate concentrations, and thermocouples were used to record the temperatures at various locations in the stove. Efficiency and other performance characteristics of the stove were calculated with reference to the fuel mass consumed and time taken to complete an assigned task. The water temperature and the flue gas temperature were measured using thermocouples attached to the pot and chimney, respectively. The data were collected at ten second intervals throughout each test. At the end of each test the data were exported to an Excel sheet for processing.

All tests were done using 5 L Hart™ aluminium pots with the lid on. Figure 4 outlines the laboratory testing summary where all sampling channels are connected to the collection hood.

Figure 4: Experimental set up for analysis of combustion process from fuel/stove

4. HETEROGENEOUS TESTING PROTOCOL

The full version of the Heterogeneous Testing Protocol was employed in this study for quantifying the thermal and emission performance of the selected devices.

The procedure contained in the protocol requires each type of fuel which will be used in testing to be analysed; first for moisture content and then for the calorific value. The formula used in measuring the thermal and emissions performance accounts for the moisture and calorific values of each fuel used.

The generic matrix and testing procedures contained in the latest version of the Heterogeneous Testing Protocol were adopted in this study to maintain the accuracy and quality of data which is reported.

The Heterogeneous Testing Protocol allows performance evaluations which take into account several variables in real-world use that could adversely affect standardised test results if not accounted for. Performance evaluation can be negatively or positively affected by feeding practice, temperature value, and fuel type and fuel particle size. Failure to control or report on these factors may cause serious deviations on performance between laboratory tests and field stoves.
5. QUALITY CONTROL

In ensuring that all reported data can be replicated and reproduced, a precise set of standard operating procedures were followed before, during and after each test. The entire sampling dilution system was assembled before testing, cleaned and tested to identify any leaks. The cleaning of the dilution system included the removal of pre-existing organic and metal compound through blowing cold air in to the system using compressed air. Some larger particles cannot be removed by compressed air therefore clean purified water was used. The collection trains including nozzles and steel pipes were cleaned with water and blown with compressed air to dry them. After quality checks the dilution system was connected to the entire testing rig for a trial run on the tests. When all necessary spot checks were concluded definitive tests commenced.

6. RESULTS

The results presented in this paper are divided in to three sections: the first reports on particulate emissions, the second reports on gaseous emissions using the CO: CO2 ratio (measure of combustion efficiency) as an indicator factor while the third report on specific fuel consumption.

6.1. PARTICULATE EMISSIONS

Table 3 shows emission profiles for particle emissions for both Basa njengo Magogo and traditional ignition methods. When employing the traditional ignition method there is a statistical significant difference at 95% confidence level when using a student T-test on the PM2.5 emissions between the high case imbaula (Imb01) and the medium case imbaula (Imb02); the high case imbaula (Imb01) and the low case imbaula (Imb03); and the medium case imbaula (Imb02) and the low case imbaula (Imb03). When employing the Basa njengo Magogo method, there is no statistical difference at the 95% confidence level when using a student t-test in the PM2.5 emitted between the medium case imbaula (Imb02) and the low case (Imb01) imbaula. These results show the influence of the air supply on the overall performance of the stove. An interesting result from these experiments indicates that the higher the ventilation rate is the more efficient the imbaula is in reducing particulate emissions. Air supplied to the stove presents an important factor in reducing or increasing emissions of PM2.5—adequate air supply lead to reduced emissions of particulates matter (PM2.5) while inadequate air supply lead to high emissions of particulate matter. When the imbaula is starved of air it releases high emissions of particles (Table 3).

Table 4 reports the effects of ignition method on particulate emissions using the same stove and fuel. The results show a statistical significant difference (at 95% confidence level when using a student t-test) on the particulate emissions between Basa njengo Magogo and traditional ignition methods. All the three stoves report a high percentage reduction in PM2.5 emissions when employing the BnM between the ignition methods compared to the traditional method – Imb01 reported 82%, Imb02 at 81% while Imb03 reported 77%. The findings support the 80% reduction in particulate matter using Basa njengo Magogo as reported by [10.8]. Nevertheless, optimal configurations need to be made to bring about a good balance between the number holes and their distribution pattern around the device.

6.2. COMBUSTION EFFICIENCY (CO: CO2 RATIO)

The high case stove (Imb01) has the lowest CO: CO2 ratio of 4% when using traditional ignition method but the very same stove reports a high CO: CO2 emissions when employing the Basa njengo Magogo ignition method, with the ratio rising to 5.7%. Although the high case stove performs better on CO: CO2 ratio when compared to the other two stoves, the ratio still does not comply with the reference value of 2% CO: CO2 ratio. In all tests the
CO: CO₂ ratio seldom drops below 2%, which is a clear indication of incomplete combustion processes.

Another interesting observation is at a later stage of combustion, just after the coal has pyrolysed, there is a steady rise in CO: CO₂ ratio. This finding shows the effects of increased excess air being fed into the stove. During smouldering, the CO: CO₂ ratio steadily increases above 4%. It will be necessary to develop a system that can control air supply to the stove at later stages of combustion. Results in Table 5 show that the traditional ignition method produces a lower CO: CO₂ ratio compared to the BnM. The traditional ignition method maintains a big flame at later stages of combustion, burning most of the remaining hydrocarbons. With Basa njengo Magogo the flame dies off once the top coal undergoes pyrolysis, resulting in a subsequent increase in the CO: CO₂ ratio.

### TABLE 5: CO: CO₂ emissions ratio for Bottom-lit and top-lit updraft (BLUD) imbaulas

<table>
<thead>
<tr>
<th>Stove tag</th>
<th>CO: CO₂ Ratio (%)</th>
<th>Statistical analysis</th>
<th>Sig @ 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imb01 (Blud) vs Imb02 (Blud)</td>
<td>4.2 ± 0.2, 4.4 ± 0.4</td>
<td>0.25</td>
<td>0.57</td>
</tr>
<tr>
<td>Imb01 (Blud) vs Imb03 (Blud)</td>
<td>4.2 ± 0.2, 5.8 ± 0.3</td>
<td>0.49</td>
<td>0.0014</td>
</tr>
<tr>
<td>Imb02 (Blud) vs Imb03 (Blud)</td>
<td>4.4 ± 0.4, 5.8 ± 0.3</td>
<td>0.61</td>
<td>0.011</td>
</tr>
<tr>
<td>Imb01 (Tlud) vs Imb02 (Tlud)</td>
<td>5.7 ± 0.2, 6.1 ± 0.2</td>
<td>0.39</td>
<td>0.29</td>
</tr>
<tr>
<td>Imb01 (Tlud) vs Imb03 (Tlud)</td>
<td>5.7 ± 0.2, 4.1 ± 0.3</td>
<td>0.51</td>
<td>0.017</td>
</tr>
<tr>
<td>Imb02 (Tlud) vs Imb03 (Tlud)</td>
<td>6.1 ± 0.2, 4.1 ± 0.2</td>
<td>0.83</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

Results reported in Table 6 compare the CO: CO₂ ratio for Basa njengo Magogo and traditional ignition methods. It can be confirmed based on these results that although Basa njengo Magogo ignition method reduces 80% of particulate emissions, the method fails to outperform the traditional method on increasing the combustion efficiency of the devices.

### Table 6: Basa njengo Magogo vs Traditional ignition method: CO: CO₂ ratio

<table>
<thead>
<tr>
<th>Stove tag</th>
<th>CO: CO₂ Ratio (%)</th>
<th>Statistical analysis</th>
<th>Sig @ 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imb01 (Blud) vs Imb01 (Tlud)</td>
<td>4.2 ± 0.2, 5.7 ± 0.2</td>
<td>0.26</td>
<td>0.0063</td>
</tr>
<tr>
<td>Imb02 (Blud) vs Imb02 (Tlud)</td>
<td>4.4 ± 0.4, 6.1 ± 0.2</td>
<td>0.36</td>
<td>0.005</td>
</tr>
<tr>
<td>Imb03 (Blud) vs Imb03 (Tlud)</td>
<td>5.8 ± 0.3, 4.1 ± 0.2</td>
<td>0.84</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

System efficiency refers to the ratio of useful energy gained by the pot divided by the original energy available in the fuel consumed expressed in percentage. Not all heat released or contained in the fuel will be used during cooking, but it is important to improve the system efficiency; so that the stove can be accepted by the users. Most of the heat will be lost to the outside if the stove has high ventilation holes. The traditional ignition method yields a higher system efficiency (Table 7) compared to Basa njengo Magogo for high case and medium case imbaula, while there was no significant difference for low case imbaula. The medium case imbaula reports highest system efficiency on traditional ignition method with an average of 10.3%. This yield is influenced by the grate height—medium case imbaula has a higher grate height, allowing for efficient heat transfer to the pot within a short distance.

Figure 5 indicates the combustion cycle from ignition to smouldering. At the ignition phase, as shown in Figure 5–A, the CO: CO₂ ratio is high. At this stage there is little visible smoke and high flame. The wood ignites first while trying to create a hot zone on top of the fuel some of the hydrocarbons escapes to the outside. Letter B in Figure 5 indicates the pyrolysis stage. At this stage the stove is ready for use. There is no visible smoke and the flame has died out. Letter C indicates the smouldering phase where ash starts building around the coal.
The overall heating efficiency as indicated on Table 8 for traditional ignition method reports high values reaching 97% compared to Basa njengo Magogo ignition method which reports high efficiency at 94%. Low case Imbula shows no significant difference on heating efficiency when using both ignition methods.

### Table 7: Comparison of overall system efficiency for traditional (BLUD) and Basa njengo Magogo (TLUD) ignition methods

<table>
<thead>
<tr>
<th>Stove tag</th>
<th>Overall cooking efficiency (%)</th>
<th>Statistical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lmb01 (Blud) vs Lmb01 (Tlud)</td>
<td>9.6 ± 0.2 9.3 ± 0.2</td>
<td>0.58 0.0086 Yes</td>
</tr>
<tr>
<td>Lmb02 (Blud) vs Lmb02 (Tlud)</td>
<td>10.3 ± 0.5 8 ± 0.2</td>
<td>0.50 0.00005 Yes</td>
</tr>
<tr>
<td>Lmb03(Blud) vs Lmb03 (Tlud)</td>
<td>9.1 ± 0.3 9.4 ± 0.5</td>
<td>0.15 0.57 No</td>
</tr>
</tbody>
</table>

### Table 8: Comparison of overall heating efficiency for traditional (BLUD) and Basa njengo Magogo (TLUD) ignition methods

<table>
<thead>
<tr>
<th>Stove tag</th>
<th>Overall heating efficiency (%)</th>
<th>Statistical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lmb01 (Blud) vs Lmb01 (Tlud)</td>
<td>97.0 ± 0.8 95.4 ± 0.9</td>
<td>0.83 0.024 Yes</td>
</tr>
<tr>
<td>Lmb02(Blud) vs Lmb02 (Tlud)</td>
<td>94.0 ± 1.3 86.7 ± 0.9</td>
<td>0.025 0.027 Yes</td>
</tr>
<tr>
<td>Lmb03 (Blud) vs Lmb03 (Tlud)</td>
<td>87.0 ± 2.5 94.4 ± 0.5</td>
<td>0.68 0.069 No</td>
</tr>
</tbody>
</table>

### Table 9: Overall fuel consumption

<table>
<thead>
<tr>
<th>Stove tag</th>
<th>Fuel burn rate [Kg/hr]</th>
<th>Statistical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lmb01 (Blud) vs Lmb01 (Tlud)</td>
<td>0.90 ± 0.8 0.70 ± 0.5</td>
<td>0.58 0.0086 Yes</td>
</tr>
<tr>
<td>Lmb02 (Blud) vs Lmb02 (Tlud)</td>
<td>0.94 ± 0.7 0.73 ± 0.9</td>
<td>0.50 0.00005 Yes</td>
</tr>
<tr>
<td>Lmb03 (Blud) vs Lmb03 (Tlud)</td>
<td>0.98 ± 0.2 0.80 ± 0.7</td>
<td>0.15 0.57 No</td>
</tr>
</tbody>
</table>

The overall specific fuel consumption reports decreased fuel consumption for Basa njengo Magogo ignition methods as compared to traditional ignition method for all stoves (Table 9). The high case stove (Lmb01) performed better than the other two stoves on fuel consumption when using either of the ignition methods. There is a need to modify the stove to reduce fuel consumption and emissions profile while obtaining the highest thermal efficiency.

### 7. CONCLUSION

An integrated approach, addressing energy efficient housing design, the supply of clean and efficient appliances together with the use of the alternative fire ignition method, is recommended to address indoor air pollution from household coal use [12]. Results from this study indicate that an increase in excess air supply (through a larger number of ventilation holes) leads to higher combustion efficiency numbers, while a decrease in excess air leads to increases in fuel efficiency. In order to obtain the best performance profile on an imbaula there must be an appropriate modification, mainly on number and spacing of primary (below grate) and secondary (above grate) air hole inlets. Although several energy interventions are suggested, while others are already introduced in low income settlements, there is a need to design and optimise an imbaula that will lead to reduced emissions and improved thermal performance.

### 8. REFERENCES


9. AUTHORS

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**Co-author:** Prof Harold Annegarn has researched atmospheric pollution, environmental management and energy efficient housing in southern Africa for 30 years. He has supervised over thirty MSc and PhD students. His current research interests are on energy and sustainable Megacities, through the EnerKey programme in partnership with the University of Stuttgart; and the development and testing of improved domestic combustion stoves, and their contribution to air pollution reduction. He is the Director of the SeTAR Centre at the University of Johannesburg, a Regional Stove Development and Testing Centre of the Global Alliance for Clean Cookstoves (GACC).

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**Presenter:** This paper is presented by Daniel Masekameni