OPTIMISING THE *IMBAULA* STOVE

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ABSTRACT

In South Africa, human and environmental health implications from domestic solid fuel combustion have spurred interest in cleaner alternative sources of energy and better combustion technologies. Field research among wood and coal burning informal settlements in Johannesburg has shown that the most prevalent mode of combustion is self-made *imbaula* (brazier) stoves, manufactured from discarded 20 L steel drums. Such stoves are made without any measure of performance optimisation, leading to fuel inefficiency and high emissions - previous field surveys have indicated that the number, size and placement of primary and secondary air inlets (taken as holes below and above the fire grate respectively) vary over a wide range, starting from an extreme with no holes below the grate [1]. Researchers at SeTAR Centre, University of Johannesburg, have set out to develop an enhanced *imbaula*, by investigating performance in terms of size and distribution of primary and secondary air inlets, and height of grate level. The test *imbaulas* are constructed out of standard 20 L drums with a height of 360 mm and diameter of 295 mm. A range of hole configurations has been designed, from which selected test configurations are fabricated for experimental evaluation of thermal and emissions properties, using the *SeTAR heterogeneous testing protocol*. The results indicate that higher hole densities (above and below the grate) lead to higher power outputs and lower specific CO emissions, but with lower thermal efficiency. Further, results indicate that adequate air holes below the grate (primary air) are more important for proper combustion in an *imbaula*; however this should be synchronised with secondary air in-lets (above the grid) in order to have congruence of all the performance criteria. This study should lead to the development of a set of criteria that can further enhance emissions reductions and fuel efficiency obtained by top-down stove ignition methods (*Basa njengo Magogo*) for *imbaula* type stoves.

1. INTRODUCTION

Energy and socioeconomic development are inextricably linked, and without a certain minimum measure of energy services, people's wellbeing is compromised. Globally, it is reported that approximately three billion people are dependent on traditional fuels (mainly biomass) for their basic energy needs [2, 3]. These fuels are burnt in inefficient stoves and open fires that do not allow for complete combustion thus impacting on human and environmental health. As a result, about 1.9 million people die annually from smoke related complications [2]. Many of these deaths could be avoided by using clean cookstoves that are optimised for energy efficiency and low emissions.

In Africa, the extent to which commercial energy replaces traditional fuels is quite low. It varies from as high as 90% in countries such as Algeria, Egypt, Libya, Mauritania, Morocco and South Africa; and less than 15% for such countries as Benin, Burkina Faso, The Central African Republic, Ethiopia, Lesotho and Uganda [4]. The development and promotion of clean burning wood stoves could help to alleviate pressure on overloaded national grid systems and provide a sustainable way of exploiting often abundant biomass resources.

Although biomass is a renewable source of energy, traditional biomass-fired stoves cause significant greenhouse gas emissions due to formation of products of incomplete combustion; also, exposure to smoke from these stoves causes serious health problems [5]. The detrimental effects of smoky indoor environments are illustrated by experimental exposure to human subjects, which caused inflammatory response and signs of increased oxidative response in the lower airways of the respiratory tract [6].

A study conducted in rural Bangladesh concluded that the incomplete combustion of biomass in the traditional cooking stove poses severe epidemiological consequences to human health and contributes to global warming [7]. Elsewhere, the introduction of an improved stove with two cooking stations and a chimney resulted in a reduction of fuel when compared to the traditional stove [8].

In South Africa, poor communities burn wood and coal in self-fabricated drum stoves (*imbaulas*) that are made from recycled 20 L containers. Such stoves lack any measure of performance optimisation leading to fuel inefficiency and high emissions. Studies have shown a correlation between high infant mortality in some South African townships and particulate emissions from coal combustion in *imbaulas* [9]. Inefficient stoves also cause people to spend a disproportionate amount of time and money in fuel gathering activities – a factor in energy poverty.

This study sets out to develop an optimised *imbaula* in terms of size and distribution of primary and secondary air inlets, and height of fire grate level. This will address the random construction tendencies where people just poke holes in the drum without aiming for a definite number and/or size.

While all stoves produce nearly the same amount of CO_2 for each kilogram of wood, the improved stoves burn cleaner, emitting less particulate matter and less CO per kilogram of wood [10]. Well designed stoves not only help improve human wellbeing, but also mitigate global warming. To ensure success in the stove market, new energy conversion technologies should be designed so as to fit into people's every day lives [11].

Optimisation of a domestic wood or coal stove involves attaining a fine-balance between combustion efficiency and thermal efficiency. Excess air in a brazier may result in better combustion efficiency but also high fuel consumption and thus poor thermal efficiency. On the other hand, decreasing the excess air in a brazier results in increased emissions of products of incomplete combustion and higher fuel efficiency; however this happens until fuel losses due to incomplete combustion become too high [12]. We hypothesise that by testing several configurations, it is possible to arrive at an optimum primary and secondary air flow. The primary air in a wood burner converts fuel carbon into CO_2, CO and particulate matter, while secondary air reduces the products of incomplete combustion to CO_2 and H_2O, if the residence time and temperature are sufficient.

2. EXPERIMENTAL DETAILS

The experimental particulars of this study are informed by field *imbaula* characterisation data that was gathered in Setswetla informal settlement, Johannesburg, from June 2009 to March 2010. The experiments are divided into two parts: part one involved designing and constructing the *imbaula* stoves, while the second part involved testing the stoves for thermal and emissions performance.

2.1 *IMBAULA* STOVE CONSTRUCTION

The definitive features for each design configuration are shown in Table 1. The fabrication process involved marking and perforating the air holes on standard 20 L metal drums with a height of 360 mm and diameter 295 mm and then setting the fire grate in place (Figure 1). In total, four *imbaula* designs (Imb01w, Imb02w, Imb03w and Imb04w) were constructed and tested for emissions and fuel efficiency (Figure 2). The first three *imbaula* stoves depicted the maximum, middle and minimum (i.e. high, middle and low case) number of air holes above and below the fire grate, as observed in the field study sample, while the fourth stove was our first design of an *improved imbaula*.

Table 1: *Imbaula* design configurations

Design	No. of holes		Grate height (mm)
	H_1*	H_2	
Imb01w (*max holes*)	40	44	117
Imb02w (*min holes*)	8	0	117
Imb03w (*med holes*)	20	12	117
Imb04w (*improved*)	32	16	140

* H_1: holes above the grate; H_2: holes below the grate

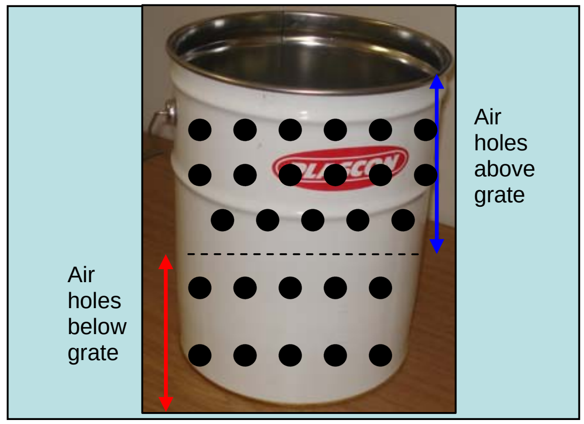

Figure 1: *Imbaula* fabrication diagram


Figure 2: Image of *imbaula* stoves (Imb01w – Imb04w)

The first three designs (Imb01w, Imb02w and Imb03w) had a uniform hole diameter of 18 mm, while Imb04w had hole diameters of 20 mm below the grate and 18 mm above the grate. Primary air was supplied into the brazier through air holes below the fire grate whereas secondary air was introduced through air holes above the grate. For the first three designs, the fire grate was set at one-third of the device height in keeping with common practice for wood burners in the study area.

2.2 STOVE TESTS

Each of the four *imbaula* stoves was tested for thermal and emissions performance based on the *SeTAR heterogeneous testing protocol* [13]; with each *imbaula* tested three times giving a total of 12 tests. The protocol required continuous measurement of fuel mass consumption, trace gas emissions and water temperature over the period from lighting the stove until a pot containing 5 L of water is brought to the boil, and for a further 15 minutes while vigorous boiling is maintained. The purpose for these tests was to quantify the fuel and time needed to bring five litres of water to the boil and CO emission factors over the burn cycle.

2.2.1 Fuel Characteristics

The *imbaula* stoves in this project were tested with air-dry sawn pine fuelwood that had the following characteristics:

- Moisture content: 8.2 %;

- Gross calorific value (dry-basis): 21.3 MJ kg^{-1};
- Approximate wood sizes: 20x20x270 mm

2.2.2 Experimental Procedure

The following experimental procedure applied during the stove tests:

- Switch on the *Testo 350-XL®* flue gas analyser; after zeroing, connect to the computer and set the probe to collect flue gases from under the vent hood (Figure 3).
- Take the masses of the pot, lid and 5 L of water, 800 g of wood and 10 g of paper. Measure the initial water temperature using a thermocouple connected through the pot lid.
- Load the wood and 10 g of paper into the *imbaula* and place on the scale under the hood. Sprinkle 15 ml of paraffin on the wood and kindle.
- After 30 seconds, zero the scale and place the pot with 5 L of water on the *imbaula*.
- Mass of water evaporated and fuel loss during the burn cycle is recorded every minute by reading from the scale and lifting the pot of water. Rise in water temperature is read from the thermocouple and time taken to reach the boil is noted.
- At end of the test, stop the flue gas analyser, export the gaseous emissions data to *Excel* spreadsheets and save. Ascertain the mass of the remaining char.
- Thermal performance was computed from *MS excel®* spreadsheets.

Figure 3: *Imbaula* test assembly

3. RESULTS AND DISCUSSION

The results are presented in two parts: (i) thermal performance of the fabricated stoves; and (ii) emissions results.

3.1 THERMAL PERFORMANCE

The *maximum holes imbaula* (Imb01w) had the highest firepower (22 550 ± 2 310 Watts) and was the fastest to boil 5 L of water at an average speed of 9.1 ± 0.8 minutes, while the *minimum holes imbaula* (Imb02w) had the lowest firepower and boiling rate as well as the worst specific CO emissions (Table 2). The *improved case imbaula* had moderately improved specific fuel consumption (126 ± 2 g L^{-1}) compared with the other configurations except the *minimum holes imbaula*.

Table 2: Task based performance for all test *imbaulas* (bring 5 L pot of water to boil; temperature corrected to 80°C rise).

Parameters	Min. Holes ∗±S.D.	Medium holes ±S.D.	Max. holes ±S.D	Improved imbaula ±S.D
Firepower [Watts]	9 830 ± 330	15 350 ± 1940	22 550 ± 2310	13 520 ± 2130
Thermal Efficiency [%]	17.4 ± 0.5	15.1 ± 0.6	14.2 ± 0.8	15.7 ± 0.4
Time to boil [min]	16.5 ± 0.7	12.5 ± 0.5	9.1 ± 0.8	13.3 ± 2
Specific Time to Boil [min L^{-1}]	3.31 ± 0.13	2.5 ± 0.1	1.82 ± 0.16	2.67 ± 0.39
Spec. Fuel Cons [g L^{-1}]	124 ± 5	138 ± 10	139 ± 3	126 ± 2
Specific CO emitted [g L^{-1}]	5.83 ± 1.29	1.16 ± 0.19	2.17 ± 1.26	2.55 ± 0.87

∗Average for three tests ±Standard deviation (S.D)

The reason why the *minimum holes imbaula* was the worst burner is primarily due to lack of primary air supply in the device, which meant that the combustion process was slow and inefficient. Overall, the stoves' thermal performance results show a linear relationship between firepower and thermal efficiency when boiling 5 L of water.

The above results have shown that high firepower tends to correspond to low thermal efficiency and high fuel consumption. However, for an improved stove to be attractive to users, it is important to balance firepower with specific fuel consumption. This can be accomplished by having a stove design that allows an optimum combustion-air stream (primary and secondary air flow).

3.2 EMISSIONS

The ratio of CO to CO_2 is an expression of the stove's combustion efficiency: the lower the ratio, the higher the completeness of combustion. The results of this study shows that the *maximum holes imbaula* had the best combustion efficiency, with the CO/CO_2 ratio (v/v) reaching a low of 1.3% ± 0.1% in the middle phase of the burn cycle (each phase of burn cycle is approximately equal to one-third of fuel mass burnt) (Table 3). On the other hand the *minimum holes imbaula* had the worst combustion efficiency (CO/CO_2 ratio (v/v) = 5% ± 2.2%), which was attained in phase 3. Signs of poor combustion in the *minimum holes imbaula* were further observable from comparatively large amounts of post-test char and tar-like droplets at the bottom of the stove. Generally, all the stoves burnt cleaner in the initial phases, especially in phase two; however, as the fuel burn rate dropped, there was a corresponding rise in CO/CO_2 ratio and overall CO mass emitted.

The grate level might have had a significant influence on the generation of CO for the configurations investigated. This is demonstrated by the *medium holes imbaula* and the *improved imbaula* that had approximately the same firepower and thermal efficiency but considerably different specific CO emissions (CO per unit mass of water boiled). The *medium holes imbaula* had the fire grate height at 117 mm, while the *improved imbaula* had the grate set higher at 140 mm, which may have offered less residence time for CO to be converted into CO_2 and HO_2.

The flue gas analyser used in this study (*Testo 350-XL®*), measures various types of gaseous emissions (e.g. CO_2, CO, H_2, H_2S, SO_2, NO and NOx). However, in wood combustion, CO_2 and CO emissions are the most significant, and equally important in terms of environmental and human health. CO_2 has implications for global warming, while CO is an insidious poison to human beings, especially in poorly ventilated spaces. The emissions data reported herein therefore focused on these two gases and their interactions with various aspects of performance.

4. CONCLUSION

Design modifications to traditional wood burning devices (e.g. *imbaula*) can lead to significant improvement in terms of CO and CO_2 emissions as well as thermal properties without necessarily incurring additional costs. Decreasing the excess air in an *imbaula* raises fuel efficiency; however, the correct balance between primary and secondary air should be sought in order to attain the best thermal and emissions performance.

Apart from improved wood/coal stove designs, a range of domestic energy interventions are needed in order to reduce the level of harmful emissions and so improve people's health and wellbeing. Such interventions may include well ventilated and thermal efficient houses and alternative cleaner fuels; and cooking/heating technologies.

This paper presents work in progress. The next phase of tests will involve additional improved configurations for wood and coal burning *imbaulas*; comparisons of top and bottom ignition; and varying grate levels.

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Table 3: Rated performance for each stove across all test phases

Test Phase	**Minimum holes case** Average ± SD (3 tests)			**Medium holes case** Average ± SD (3 tests)			**Maximum holes case** Average ± SD (3 tests)			**Improved Imbaula** Average ± SD (3 tests)		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Firepower [Watts]	11 710 ±1 380	10 620 ±1 340	3 530 ± 170	17 640 ±1 730	23 490 ±3 270	4180 ± 150	21 010 ±3 560	38 950 ±5 390	5 750 ±1 060	16 630 ±3 290	20 930 ±3 990	4 790 ±170
Thermal Efficiency [%]	16.2 ± 1.8	17.4 ± 0.7	24.4 ± 1	15.2 ± 3.6	13.7 ± 2.4	26.3 ± 4.1	13.2 ± 0.8	15.1 ± 2.1	24.1 ± 6.2	18.6 ± 6.6	14 ± 4.4	27.5 ± 1.5
Burn Rate [g h^{-1}]	2.67 ± 0.29	2.43 ± 0.37	0.81 ± 0.05	3.82 ± 0.41	5.08 ± 0.63	0.9 ± 0.02	4.3 ± 0.7	7.98 ± 1.05	1.18 ± 0.23	3.53 ± 0.68	4.44 ± 0.82	1.02 ± 0.03
CO/CO_2 ratio [%]	5 ± 1.1	4.7 ± 2.2	5.1 ± 2.2	0.8 ± 0.1	1.6 ± 0.5	3.8 ± 0.4	1.6 ± 0.9	1.3 ± 0.1	2.9 ± 0.2	2.1 ± 0.7	1.8 ± 0.8	4.8 ± 0.4
CO (EF) [g MJ^{-1}]	2.98 ± 0.58	2.82 ± 1.34	3.04 ± 1.32	0.5 ± 0.04	0.93 ± 0.29	2.18 ± 0.24	0.89 ± 0.51	0.75 ± 0.06	1.61 ± 0.14	1.19 ± 0.4	1.02 ± 0.44	2.69 ± 0.24
Turn Down Ratio†		3.7			6.5			9.7			5.4	

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† Turn Down Ratio is Max/Min firepower across all tests for same stove

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The paper will be presented by David Kimemia.