CHARACTERISATION OF DOMESTIC BIOMASS COMBUSTION TECHNOLOGIES USED IN SETSWETLA, ALEXANDRA TOWNSHIP, GAUTENG

D.K. Kimemia, H.J. Annegarn, T. Makonese, V. Molapo and J. Robinson
University of Johannesburg, Johannesburg, South Africa

ABSTRACT

There are sections of urban society in the Gauteng mega-city that are wholly dependent on biomass fuel, both in the household as well as in subsistence economic activities. Use of poor combustion devices is seen as a major cause of the energy burden and high incidence of indoor and ambient air pollution in the biomass-using communities. This study characterises the biomass combustion technologies (*imbaulas*) used by this socio-economic stratum of Gauteng mega-city residents, using Setswetla village in Alexandra Township as a case study. The study also tests the thermal performance and emissions of typical in-service *imbaulas* against that of an improved stove, the *GreenFire* (*Rocket*) stove. The findings indicate that most biomass burning is done in an *imbaula*, which is a device with variable construction and with no standardised operational procedures. The stove test results indicate that the *GreenFire* improved stove has higher thermal efficiency and lower emissions than the conventional imbaula. This study concludes that the adoption of improved stoves, such as the *GreenFire*, could lower the energy burden of Setswetla residents leading to improved quality of life and poverty alleviation.

1. INTRODUCTION

Although biomass use in South Africa is mostly concentrated in un-electrified rural areas, there are pockets of biomass dependent communities in the urban landscape of South African cities. Such communities are concentrated in the townships and specifically in what are commonly referred to as shacks or informal settlements. It has been noted that "*large urban slums frequently characterise the rapidly expanding cities of developing countries*" [1]. People living in these informal settlements have difficulty affording coal or LPG fuels. They depend on biomass energy resources that are collected within and without the settlement areas and sometimes bought from firewood vendors. Occasionally, these households may use paraffin as a substitute fuel for household cooking. However, biomass forms the bulk of their energy sources and is mainly used for space heating and business cooking.

One such biomass dependent informal settlement is Setswetla, which is located barely 5 km from Sandton, which is the financial heart of Gauteng and South Africa. These informal settlement dwellers are cut-off from the formal energy economy that is driven by electrical energy and hence cannot even access the Free Basic Electricity (FBE) that is given to indigent families. The wood that is collected by these poor people is burnt in *imbaula* stoves which are energy inefficient. Thus, much time and energy is expended in making repeated trips to collect firewood.

The *imbaula* stoves are characterised by their various operational parameters, for example, the number and size of holes and whether the device has a grate or not. Our preliminary surveys have shown that there is nothing like a *standard imbaula*, as the devices vary greatly, even when they are made from same size of container. This study has surveyed the various sizes and parameters of *imbaula* stoves that were encountered during a household energy survey in Setswetla, Alexandra, informal settlement [2]. Such data will inform on the types of domestic biomass combustion technologies used in dense urban settlements and therefore assist in the design of appropriate intervention measures.

Since poor people will continue to rely on biomass energy resources, it is imperative to design better combustion technologies in order to address the ubiquitous energy poverty in African megacities and in rural communities. It is postulated that "*wood burning-stoves can, in theory, be GHG neutral if wood undergoes complete combustion and if an equivalent amount of wood is grown to replace the wood that is burnt*" [3]. "*Efficient technologies for the use of biomass would, therefore, ensure that scarce biomass resources are effectively utilised, and reduce the negative impacts of biomass use on women and children's health*" [4].

Within a country or region, there are many factors that contribute to household fuel choice, for example, "*…access to fuels and residential energy technologies, household income and ... important socio-cultural preferences affecting household behaviour and cooking preferences*" [3]. "*The fact that wood fuel remains so prominent in the energy mix of rural households, suggests that we cannot ignore woodfuel even when the national agenda is very much taken up by 'modern' energy*" [5].

In order to enhance the better exploitation of biomass energy resources, the South African Government is supporting initiatives in the development of appropriate combustion technologies and the *Basa Njengo Magogo* alternative fire lighting method. This is in recognition of the fact that biomass fuel provides the basic energy for majority of the poor and the fact that a "*shortage of energy severely restricts the improvement of people's living standards*" [6]. It is also recognised that "*…the bulk of savings due to reduced pollution from combustible fuels would go to government, primarily due to reduced spending in public health care*" [7]. This point is vindicated by a South African study, which highlights that the "*…use of biomass fuels in open fires or poorly functioning stoves, often with inadequate ventilation is the primary cause of indoor air pollution*" [8].

"*Suspended particulate matter and carbon emissions from the combustion of biomass, in addition to their environmental consequences, have been casually associated with the incidence of respiratory and eye infections*" [9]. Improved stoves offer the potential for emission reduction, as demonstrated by studies in Kenya that showed the "*…introduction of improved wood-burning stoves led to reduction of average suspended particulate matter concentration by 48% during the active burning period and by 77% during the smouldering phase*" [9]. Various studies also show that the installation of improved cookstoves may result in significant reductions in indoor concentrations of carbon monoxide and fine particulate matter ($PM_{2.5}$) [10; 11; 12]. "*Fuel efficiency and pollution emitted from biomass stoves therefore have important implications for a number of important, interrelated aspects of development, including health promotion, protection of the environment, and the household economy*" [13].

"*Since reduction in fuel use is perhaps the most compelling reason for consumers to adopt an improved stove, there is a need to understand the fuel use of a proposed stove as well as the performance of existing in-place stoves*" [14]. This knowledge is necessary "*…to evaluate the environmental benefits of stove introduction; particularly those related to reduction of deforestation and direct greenhouse gas emissions*" [14].

It is common knowledge that wood gathering exerts an enormous burden on poor people's lives and therefore fuel saving is the most needed feature of improved stoves. This is exemplified by reports from Mexico and Mali which indicate that "*…in rural Mexican communities, people spend an average of 15-20% of their income purchasing fuelwood*" [15], while in Mali "*...rural women spend more than two hours a day, on average, finding wood*" [16]. A recently concluded study in Setswetla informal settlement also indicates that residents travel an average of two kilometres and spend up to two hours in search of firewood, a chore that is repeated at least twice a week [2].

Because South African case studies on comparative biomass stove performance data remains elusive, it seemed desirable to test and compare the performance of in-service *imbaulas* and improved biomass stove. Consequently, in the study presented in this paper, we tested under a standard protocol (the University of Johannesburg SeTAR Centre *heterogeneous testing protocol)* [17], the regular 20 litre drum *imbaula* and the improved *GreenFire* (*Rocket*) stove.

2. METHOD

2.1 IMBAULA CHARACTERISATION

This paper presents part of a wider project on household energy survey that was carried out in Setswetla in August 2009. During the field survey, permission was sought from each of the respondents to photograph and measure all the defining dimensions of their *imbaula* (e.g. height, diameter, number and size of holes above and below the grate). Figure 1 shows the *imbaula* characterisation diagram. A total of 40 *imbaulas* were characterised and photographed. The data are presented in the results section.

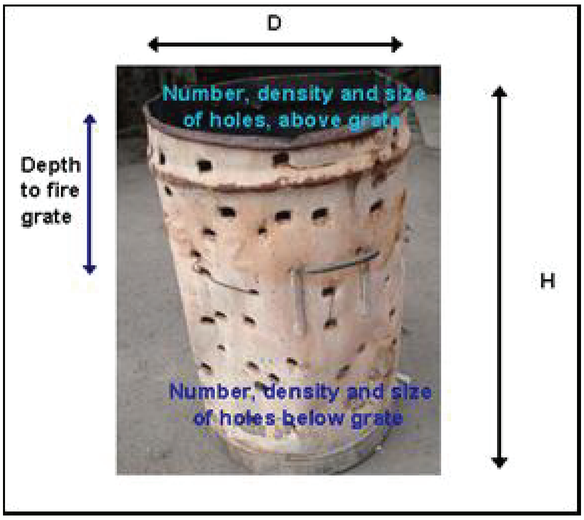


Figure 1: *Imbaula* characterisation diagram

2.2 STOVE TESTING

Two stoves, one a regular imbaula bought in Alexandra and a sample of improved biomass stove (*GreenFire*, from China) were tested for thermal and emissions performance. The tests were carried out at the SeTAR Centre testing laboratory located at the Faculty of Arts, Design and Architecture, University of Johannesburg. The purpose for these tests was to determine the stove combustion efficiency at high power and simmering settings, trace gas emission factors, and general operational features (e.g. smokiness and ease of start-up).

The testing equipment used for this study was a *Testo 350-XL,* portable gas emissions analyser. Connected to the Testo 350-XL machine was a computer for capturing all test data. Other apparatus include an emissions capturing hood, digital mass scale (for weighing the pots, water and fuelwood), and a thermocouple sensor (to record water temperature) (Figure 2). An oven drier was used to dry a sample of firewood for the purposes of calculating the moisture content of the wood fuel. A sample of the same wood fuel and post-test charcoal was taken for analysis of energy content in a bomb calorimeter

(CAL^{2K} ECO CALORIMETER) at University of Johannesburg Mechanical Engineering Department.

The *SeTAR heterogeneous testing protocol* was the one adopted for these series of tests (Pemberton-Pigott *et al.*, 2009). The testing data were analysed for the following parameters: time taken and fuel mass used to boil five litres of water; energy expended in boiling five litres of water; average amount of carbon monoxide (CO) emitted to boil five litres of water; and the stove thermal efficiency.

Figure 2: Stove testing apparatus

2.2.1 Summary of stove testing procedure

The following experimental procedure was applied during stove testing:

- Equipment setup: Set up the *Testo 350-XL* with the probe to measure flue gas and emissions of NO_x (NO and NO_2), CO, O_2, CO_2, SO_2, H_2S, hydrocarbons and other parameters. Connect *Testo 350-XL* analyser to a computer. The probe is set to collect flue gases from the hood under which the stove and pot assembly is set.
- Pre-weigh the pot plus its lid, five litres of water, fuelwood and the stove;
- Place wood in the stove and sprinkle 10 ml of paraffin on the wood, then kindle;
- After the wood has properly ignited, which takes about 3 minutes, place the pot with water on the stove;
- Measure and record the temperature of water through a thermocouple placed in the pot (from cold start up to the end of test).
- During the experiment, the stove set-up remains on the weighing scale to continuously monitor fuel loss and water evaporation. This weight loss is recorded every minute by reading from the weighing scale as well as lifting the pot of water.
- After the water has boiled, stop refuelling and simmer with the remaining charred wood/charcoal, while keeping the two doors of the GreenFire stove two-thirds closed. Simmering for *imbaula* is done the same way except there are no provisions for controlling the excess air. Simmering is done until there is no more change in fuel mass or the temperature of water starts reducing.

At the end of the test, measure the amount of fuel that remains, whether unburnt wood or charred wood/charcoal. Final mass of the stove is also taken to determine any changes. The amount of fuel used up by the stove to boil the water is then ascertained, while its thermal performance is derived from set equations in template spreadsheets.

Each stove (i.e. imbaula and GreenFire) was tested three times, making a total of six tests. The performance for each stove was taken as the average of the three tests.

3. RESULTS

This section presents results from this study. The results are presented in three parts. The first part describes the different types of biomass combustion technologies in Setswetla; the second part presents *imbaula* characterisation data, while the last section presents the stove test results.

3.1 BIOMASS COMBUSTION TECHNOLOGIES IN SETSWETLA

The common biomass combustion technologies in Setswetla are various sizes of self-fabricated stoves popularly referred to as *imbaula* and the 3-stone open fire place (Figure 3). As shown in Figure 3, *imbaula* A has only a few holes and no grate while B has many more holes plus a grate. This depicts the great variations inherent in imbaula devices. Other less common biomass combustion technologies in Setswetla are the Braai stands that are predominantly used for business cooking. A majority of the respondents in Setswetla (83.9%) indicate that once broken, an *imbaula* cannot be repaired, it is just thrown away. On average, an *imbaula* device lasts for approximately six months.

Figure 3: Biomass combustion technologies:
(A) 20 litre *imbaula;* (B) 70 litre dustbin type;
(C) 100 **l** half-drum; & (D) 3-stone open fire place

3.2 *IMBAULA* CHARACTERISATION RESULTS

Forty *imbaulas* were encountered in the total sample of 103 interviewed households and each of these devices had their height, diameter, number of holes and average size of the holes quantified. Also noted was whether the imbaula had a grate or not. The *imbaulas* are characterised into three classes according to the volume of device (i.e. 20 litre paint container, 70 litre metal dustbin and 100 litre half-drum). Notice that there is nothing like a standard *imbaula* as the devices vary greatly in terms of number and size of the side holes and whether the *imbaula* has a grate or not.

Various descriptive statistics for the sampled *imbaulas* are shown in Table 1. Notice that the minimum height recorded was 180 mm while the maximum height was 640 mm with an overall mean height of 375 mm. Likewise, the minimum diameter was 170 mm with a maximum of 590 mm and a mean of 298 mm. The mean hole size was 290 mm^2, with a minimum of 40 mm^2 and maximum of 1 760 mm^2. The maximum number of holes in the sampled *imbaulas* was found to be 274 with a mean of 63 ± 52, depicting great variability of this *imbaula* parameter. The commonest type of *imbaula* is the 20 litre paint container which was found in 33 out of 40 cases, equal to 83% frequency. This small size of *imbaula* is used in the households while the business owners prefer the bigger sizes.

Table 1: Imbaula characterisation statistics

	Descriptive Statistics			
Parameter	Min	Max	Mean	Std Dev
Height (mm)	180	643	375	69
Diameter (mm)	170	590	298	71
Average hole-size (mm^2)	40	1 760	290	278
Number of holes	13	274	63	52

3.3 IMBAULA AND GREENFIRE STOVE PERFORMANCE RESULTS

The *GreenFire*, previously referred to as the *Rocket stove*, was imported from China on a trial basis. It is marketed by StoveTec, which is the commercial side of operations of the Approvecho Research Centre. This is a biomass stove that burns wood or charcoal (Figure 4). In this study, the *GreenFire* as well as the *imbaula* were tested with sawn pine firewood which had average moisture content of 10.1% and a calorific value of 19.4 MJ/kg. Charcoal residues from combustion of the same wood had a calorific value of 31.3 MJ/kg.

Figure 4: Image of *GreenFire* (Rocket) stove

The *imbaula* used for these tests was the regular 20 litre metal paint container that had a grate. It had the following characteristics (Figure 5):

- Total number of holes: 140
- Average hole surface area: 200 mm^2
- Height of grate level: 140 mm
- Number of holes: 44 below the grate; 70 above; and 26 on the grate
- Height of device: 370 mm
- Diameter of device: 300 mm.

Figure 5: Typical Highveld imbaula stove

The stove test results show that the *GreenFire* used 57.4 g/litre to bring the pot of water to the boil, while the *imbaula* used 108.7 g/litre of fuel for the same task. The results also show that the *GreenFire* used 0.99 MJ/litre, while the *imbaula* used 1.81 MJ/litre. (Table 2). The thermal efficiency of the *GreenFire* stove is 100% better than the *imbaula.* Notice that the *imbaula* also simmered for a far shorter time than the *GreenFire* stove. At the end of the test the *GreenFire* had about one gram of charcoal remaining while the *imbaula* had an average of 30 g. Overall, this depicts that the GreenFire is a more efficient combustion device than the *imbaula*.

Thermal efficiency of the *imbaula* was found to be 15%, while the GreenFire stove showed an average thermal efficiency of 37%. At high power both stoves burned cleanly, however, as the flame died out during low power phase (simmer), the CO emissions gradually increased for both.

Table 2: Averaged imbaula and *GreenFire* stove test results

Parameters	Type of stove	
	GreenFire	*Imbaula*
Fuel used to boil 5 litres of water (g)	287	543.5
Time to boil 5 litres (minutes)	24	22
Energy to boil water (MJ/litre)	0.99	1.81
CO emitted to boil (g/litre)	1.10	2.40
Simmer duration (minutes)	24	n/a
Thermal efficiency (%)	36.7	15

3.4 DISCUSSION OF RESULTS

The results show that an *imbaula* is variable in terms of number and size of side holes and whether the device has a grate or not. This means there is nothing like a standard imbaula as the features differ greatly even where the devices are fabricated from similar containers. This information has implications in assessing the performance of *imbaula* as different devices might perform very differently. The particular *imbaula* used in this study's stove testing experiments had adequate side holes and a fire grate.

The stove test results showed that the *imbaula* used 83% more energy than the GreenFire to boil a litre of water, and also recorded a thermal efficiency and CO emissions twice that of the improved stove. The main problem with an imbaula is in its construction, whereby holes are poked at random without aiming for a definite number or size. Although these holes help to increase air flow during start-up, they also lead to high fuel wastage and low efficiency due to excess air. During the simmering phase, it is impossible to control the excess air in *imbaula* and therefore the remaining fire from charred wood and the stove's radiant heat are quickly used up. This reduces the *imbaula* simmering potential and thermal efficiency. These results clearly show that the *GreenFire* improved stove is more energy efficient than an ordinary *imbaula*.

4. CONCLUSION

Based on the foregoing, it can be concluded that the common biomass combustion technology in Setswetla informal settlement is the 20 litre *imbaula* drum. The *imbaula* has been found to be a variable device with no optimisation of operational parameters. As shown by the stove test results, the *imbaula* stoves are less energy efficient and have higher emissions than the *GreenFire* (Rocket) improved stove. Adoption of stoves such as the *GreenFire* can therefore lead to a significant saving in the amount of firewood needed to perform specific fire-related tasks and also reduce exposure to harmful products of biomass combustion.

5. ACKNOWLEDGEMENTS

This study was supported by the University of Johannesburg Quick Wins Grant and the NRF Focus Area Grant *Sustainability Studies Using GIS & Remote Sensing (FA2005040600018)*. I also acknowledge the University of Johannesburg's SeTAR Centre, supported by the GTZ ProBEC programme, for permission to use the stove testing equipment. Also acknowledged herewith is the assistance given by my colleagues during the field data collection exercise and laboratory experiments. My appreciation also goes to the residents of Setswetla who not only answered the enumerators' questions but also allowed us to measure and photograph their *imbaula* stoves.

6. REFERENCES

[1] Ballard-Tremmer, G. (2009), "Urban energy: a rapidly expanding issue". Article published by *Household Energy Network* (HEDON) newsletter.

[2] Kimemia, D. (2009), *Biomass alternative urban energy economy: case of Setswetla, Alexandra Township, Gauteng*. Unpublished MSc dissertation, University of Johannesburg.

[3] Bailis, R. (2004), "Wood in Household energy use". *Encyclopaedia of Energy*, *6*, 509-526.

[4] Karekezi, S., & W. Kithyoma (2002), "Renewable energy strategies for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa?" *Energy Policy*, *30*, 1071-1086.

[5] Aitken, R. (2007), "Household energy use: a comparison of household energy consumption and expenditure across three provinces". *Journal of Energy in Southern Africa*, *18*, 20-28.

[6] Li, G., S. Niu, L. Ma & X. Zhang (2009), "Assessment of environmental and economic costs of rural household energy consumption in Loess

hilly region, Gansu Province, China". *Renewable Energy*, *34*, 1438-1444.

[7] Scorgie, Y., L. Burger, H. J. Annegarn and M. A. Kneen (2004), *Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion.* Final report to the DTI NEDLAC Committee, Airshed Planning Professionals, Midrand, South Africa.

[8] Rollin, H., A. Mathee, N. Bruce, J. Levin, & Y. von Schirnding (2004), "Comparison of indoor air quality in electrified and un-electrified dwellings in rural South African villages". *Indoor Air*, *14*, 208-216.

[9] Ezzati, M., B. Mbinda & D. Kammen (2000), "Comparisons of emissions and residential exposure from traditional and improved cookstoves in Kenya". *Environmental Science and Technology*, *34*, 578-583.

[10] Cynthia, A., R. Edwards, M. Johnson, M. Zuk, L. Rojas, R.D. Jimenez, H. Riojas-Rodriguez & O. Masera (2008), "Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico". *Indoor Air*, *18*, 93-105.

[11] Zuk, M, L. Rojas, S. Blanco, P. Serrano, J, Cruz, F. Angeles, G. Tzintzun, C. Armemdariz, R.D. Edwards, M. Johnson, H. Rodriguez & O. Masera (2006), "The impact of improved wood-burning stoves on fine particulate matter concentrations in rural Mexican homes". *Journal of Exposure Science & Environmental Epidemiology*, *17*, 224-232.

[12] Smith, K.R, K. Dutta, C. Chengappa, P.P.S Gustan, O. Masera, V. Berrueta, R. Edwards, R. Bailis & K. N. Shields (2007), "Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the Household Energy and Health Project". *Energy for Sustainable Development*, *XI (2)*, 5-18.

[13] Boy, E., N. Bruce, K.R. Smith & R. Hernandez (2000), "Fuel efficiency of an improved wood-burning stove in rural Guatemala: implications for health, environment and development". *Energy for Sustainable Development*, *IV (2)*, 23-31.

[14] Granderson, J., J.S. Sandhu, D.Vasquez, E. Ramirez, K.R. Smith (2009), "Fuel use and design analysis of improved wood burning cookstoves in the Guatemalan Highlands". *Biomass and Bioenergy*, *33*, 306-315.

[15] Berrueta, V.M., R.D. Edwards & O.R. Masera (2008), "Energy performance of wood-burning cookstoves in Michoacán Mexico". *Renewable Energy*, *33*, 859-870.

[16] Bugaje, I.M. (2004), "Renewable energy for sustainable development in Africa: A review". *Renewable and Sustainable Energy Reviews*, *10*, 603-612.

[17] Pemberton-Pigott C., J. Robinson, H.J. Annegarn (2009), "Stove testing in South Africa: heterogeneous testing protocols for emissions and thermal performance", *Asean-US Next-Generation Cook Stove Workshop*, Bangkok, Thailand, 16-20 November 2009.

7. AUTHORS

Principal Author: Mr. Kimemia holds a BSc degree in Wood Science and Technology from Moi University in Kenya and a BSc (Hons) in Geography from University of Fort Hare. At present he is reading for an MSc in Environmental Management at the University of Johannesburg. Current research interests are on sustainable energy and environmental management issues. dkimemia@gmail.com

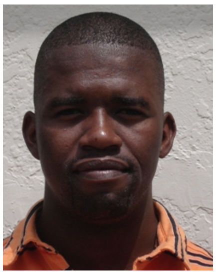
Co-author: Professor Harold Annegarn has researched atmospheric air pollution, environmental management and energy efficient housing in Southern Africa for 30 years. He has supervised over thirty MSc and PhD students. His current research interests are on energy and sustainable Mega cities, through the Enerkey programme in partnership with the University of Stuttgart; and the improvement and testing domestic combustion stoves, and their contribution to air pollution reduction. hannegarn@gmail.com

Co-author: James Robinson is a researcher, laboratory manager and PhD candidate at the SeTAR centre, University of Johannesburg. He has a background in engineering and renewable energy with experience in small scale energy projects in Africa and UK. He has experience in the research operation, engineering and development of various technologies, including stoves. jamesrobinson77@gmail.com

Co-author: Tafadzwa Makonese holds a BSc (Hons) degree, with distinction, from the Midlands State University, Zimbabwe. He is currently reading for an MPhil Energy studies degree, University of Johannesburg. His main focus is on trace gases and particulate emissions from domestic cooking devices, as well as development of standard testing protocols for different

stove/fuel combinations. taffywandi@gmail.com

Co-author: Vincent Molapo holds a National Diploma from Tshwane University of Technology. He has worked as a junior Tooling Engineer at Institute for Advanced Tooling (IAT) and also as a mechanical designer for a reputable design company, ReadyMade. He is currently working for Sustainable Energy Testing and Research Centre (SeTAR) as a stove testing and research officer. molapotv@gmail.com



Presenter: The paper is presented by David Kimemia.