

Design and performance evaluation of wood-burning cookstoves for low-income households in South Africa

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Abstract

Many cookstove programmes implemented around the world aimed to reduce fuel consumption and pollutant emissions through the dissemination and adoption of improved cookstoves. A study was carried out for the design of wood-burning cookstoves for low-income households in South Africa by employing user-centred design and co-design/co-creation approaches. Six designed variants of the biomass stove were constructed. Water-heating and emissions tests, using black wattle wood, were conducted to evaluate them for thermal and emissions performance. The large hopper stove with two secondary air inlets ranked highest, with best performance regarding thermal and emissions parameters. It outperformed the small hopper stove in time to boil, heat flux and firepower, although the latter had higher thermal efficiency values. Fuel consumption rates were high in large hopper stoves compared with small hopper stoves, resulting in increased firepower. The experimental work showed the need for iterative designing and testing of cookstoves for emissions and thermal performance to identify efficient and less polluting candi-

date stoves for dissemination in low-income communities.

Keywords: heterogeneous stove-testing protocols; thermal efficiency; emissions performance; design and development; natural-draft cookstoves

Highlights

- Design and development of an efficient wood-burning stove
- User-centred design and co-design/ co-creation were employed
- Large hopper stoves had better thermal and emissions performance
- Recommendations for contextual testing of the candidate stove

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1. Introduction

About three billion people around the globe currently depend on solid fuels such as woody biomass, charcoal, coal, agricultural residues and animal waste to meet their cooking and heating requirements [1, 2]. The 2006 International Energy Agency report indicated that over 52% of people in developing countries rely on solid biomass for cooking, most of them in countries such as India, China and Indonesia [3]. The proportion is, however, highest in sub-Saharan Africa (SSA), where over 90% of the population in rural communities relied on biomass as a primary energy source for cooking [3, 4]. Biomass fuels will continue to be a survival commodity for most households in SSA because of the unavailability and erratic nature of grid power supply, as well as the high cost of alternative energy carriers such as liquefied petroleum gas (LPG) [5]. Poor households in some SSA countries where electricity access is high, such as in South Africa, are likely to continue using solid fuels as they cannot afford electricity [6]. Electricity in these communities is used for lighting and entertainment, but not for cooking or space-heating [7].

Traditional cookstoves such as the three-stone fire are inefficient and polluting, leading to respiratory complications and other diseases [4]. Biomass can be combusted in modified cookstoves with a fixed bed combustion of fuel pieces, where combustion air flows beneath the bed by natural draft ventilation. Natural draft stoves are widely used in many household energy systems (cooking and heating stoves) in SSA, and such combustion systems include the Jiko stove (Kenya), the Pulumusa stove (Zambia) and the Tsootso stove (Zimbabwe). In the interior provinces of South Africa, the majority of low-income households combust biomass in braziers [8-10]. Braziers are made from metal drums with roughly punched ventilation holes around the sides and are colloquially known as *imbaulas* [11, 12]. They are used extensively for cooking and space-heating during the austral winter (May-August), resulting in indoor and ambient air pollution [13, 14]. The levels of combustion suspensions are unusually high on cold days with little wind, especially when low-lying inversion layers suppress mixing/dilution of the boundary layer atmosphere [15].

Residential solid-fuel combustion in the developing world has been identified as a significant source of carbonaceous aerosols, fine particle mass emissions, particulate polycyclic aromatic hydrocarbons and gaseous pollutants such as volatile organic compounds [16, 17]. Fine and ultrafine particulate matter emissions from biomass combustion are receiving significant attention from both regulatory authorities and environmental scientists because of their effects on health [18-19] and the environment, especially concerning radiative forcing [20, 21].

Emphasis is placed on optimising the performance of a biomass fuel/stove combinations to reduce emissions and improve energy efficiency, given the problems associated with the continued use of biomass fuels in traditional cookstoves. In other parts of the world, such as Asia, there was a strong drive to promote improved cookstoves from the early 1980s [2]. The Chinese National Improved Stoves Programme, for example, is recognised as the largest stove promotion programme, having disseminated 129 million stoves from 1980 to 1992 [2]. There has been renewed interest from various organisations through the advent of the Global Alliance for Clean Cookstoves (GACC) in recent years to develop improved biomass cookstoves to help meet the GACC's mandate of providing over 200 million improved cookstoves and clean fuels to marginalised countries and communities [22]. This impetus led to the development of a new generation of cookstove designs, some employing the 'rocket elbow', e.g., StoveTec designed by Aprovecho [23]. Other models use heating with natural draft [24, 25]. Modern configurations have adopted thermoelectric generators for driving air-supply fans and generating electricity for charging solar lanterns and cell phones [26, 27].

Design of cookstoves has significantly grown from being an art involving trial and error or iterative design principles to a more complex scientific and engineering exercise including the use of mathematical models such as finite element analysis and computational fluid dynamics [4]. The methods of evaluating the performance of fuel/stove combinations have been continuously developed and updated [28]. The development of testing methods, protocols and standard operating procedures require sound scientific understanding for the entire cookstove programme to be effective [4]. Further improvements in the stove design field require a bottom-up approach involving a variety of groups with a willingness to learn from past cookstove projects' successes and failures. The lessons learnt would then provide a platform to employ scientific and engineering solutions to existing problems and allowing the user to choose from a suite of options [29].

The present study aimed to design and develop a wood-burning cookstove for low-income areas in South Africa using a participatory bottom-up approach. This approach increases the chances for the adoption of improved cookstoves compared with programmes where the cookstoves are developed without considering the cooking practices and user behaviours of target communities [30]. The study also aimed to evaluate the stove for energy and heat utilisation, specific fuel consumption, time to boil, fire ignition time, emission performance, and safety aspects.

2 Materials and methods

2.1 Material

Fuels and fuel analysis

The stoves were tested for thermal and emissions performance using black wattle wood (*Acacia mearnsii*) purchased from local merchants. The wood was first characterised by conventional analysis, which is essentially the proximate and ultimate or elemental analyses. Proximate analysis measures the moisture, volatile matter, ash yield and fixed carbon content (determined by difference), while the ultimate analysis measures carbon, hydrogen, nitrogen and oxygen (determined by difference). These tests were carried out at an independent South African National Accreditation System accredited laboratory – Bureau Veritas Inspectorate. The wood was cut into uniform length sizes (400 mm) to minimise variability due to changes in airflow resistance in the packed bed resulting from non-uniform wood sizes. Each batch of the black wattle was analysed for moisture content before testing. The fuel samples were analysed on an air-dried basis, and the proximate and elemental analyses of the fuel are presented in Table 1.

Table 1: Characterisation of the black wattle wood fuel on an air-dry basis.

<i>Proximate analysis (dry basis)</i>	<i>Weight (%)</i>
Ash	0.5
Moisture (%)	6.0
Volatile matter (%)	64.0
Fixed carbon (%)	29.6
<i>Elemental analysis (dry ash-free basis)</i>	
Sulphur	0.05
Hydrogen	6.5
Carbon	49.2
Oxygen (by difference)	42.8
Nitrogen	1.5
Calorific value (MJ/kg)	18.7

Cooking pots and the use of pot lids

Hart™ aluminium 6 L capacity pots, commercially available and widely used for cooking in South Africa and regionally, were used in the experiments. For the water-heating task, an amount of water (5 L for the large pots) was heated from ambient temperature to the target temperature (about 70 °C), not higher – to prevent losses through evaporation [6]. When the water temperature reached 70 °C the pot was swapped with a fresh 5 L pot of water. This method was repeated as many times as possible until the burn sequence was completed. The pot swapping method has the potential to give a correct assessment of the thermal parameters of the stove, minimising evaporative losses and errors inherent in trying to maintain water simmering at 3–6 °C below boiling. A simmer is challenging to maintain

and requires the user to fiddle with the controls or the burning fuel to adjust the firepower of the stove, causing the water temperature to fluctuate. Legitimate questions arise about the usefulness of this metric.

The pot was used together with the lid to minimise evaporative losses, which would complicate the energetic calculations resulting in high fuel consumption rates and low efficiency numbers. It was imperative to minimise or divert the steam from the pot from the combustion flow to protect the experiment from extraneous factors [6].

2.2 Methodology

Participatory bottom-up approach

The study adopted a participatory bottom-up approach to understand the context of use of the cooking devices including cooking practices and user behaviours. This approach can potentially lead to the development of socially and technologically appropriate solutions [29], which in turn lead to widespread adoption rates and long-term sustainable uses of the technologies [30]. The stove development project followed a user-centered design process combined with co-design workshops to include end-users as decision makers in appropriate phases of the development. The co-design method followed typical design processes that included problem identification and understanding of local context. This was followed by a precedent study of existing and in-use cookstoves, reference material analysis, design and local manufacturing of a suite of prototype cookstoves, field experimentation of the designed cookstove prototypes, and performance improvement of existing prototypes [29]. Co-design workshops were set up, while ensuring direct interactions with the end-users at every stage of the process. A detailed description of the co-design stages is presented elsewhere [29].

System design

Energy efficient and less polluting biomass cookstoves were designed and fabricated at the Faculty of Art, Design and Architecture of the University of Johannesburg, South Africa, to meet the cooking and heating requirements of a household of up to six members. The computer-aided drawing schematics of the stoves are shown in Figure 1. The stove is made from 25 L galvanised iron paint containers and iron tubes. The basic design of the biomass stove is a derivative of the ‘rocket stove’ concept, with modifications in the shape of the fuel hopper, number of secondary air inlets, size of the combustion chamber, and the presence of a removable ash collector [23]. A novel feature of the biomass stove that distinguishes it from similar designs is the presence of an additional metal sleeve surrounding the primary combustion chamber, as shown in Figure 2. The sleeve allows primary air to

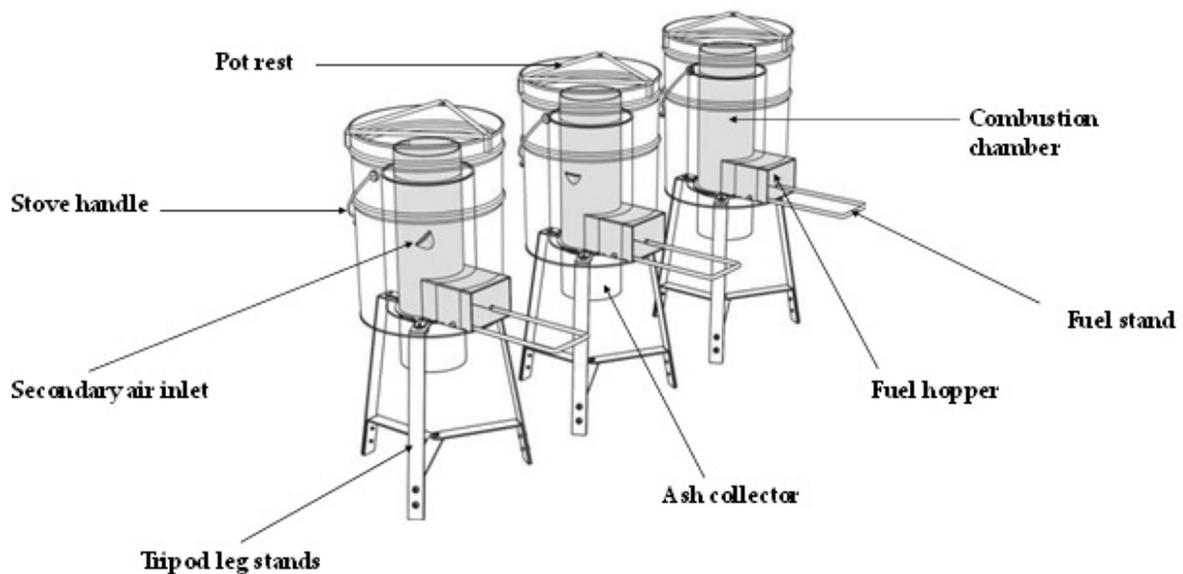


Figure 1: Computer-aided drawing of the biomass stoves highlighting various parts of the stoves.

be heated before being reintroduced into the combustion chamber, above the fuel bed, as secondary air. Heated secondary air is a prerequisite for improved combustion efficiency and emissions reduction.

Figure 2 shows the inside view of the stove from the top. A galvanised metal sleeve jacket, placed approximately 50 mm from the walls of the combustion chamber, surrounds the entire combustion chamber. The gap between the outer surface of the metal sleeve and the stove body is approximately 50 mm, ensuring that the outer surface of the stove reaches a maximum temperature of 40 °C during normal stove operation, which is an important safety feature to enhance user-acceptance. Two variants were constructed for evaluation, with the rocket-type inner cylinder/stove diameters of 127 and 101 mm, respectively.

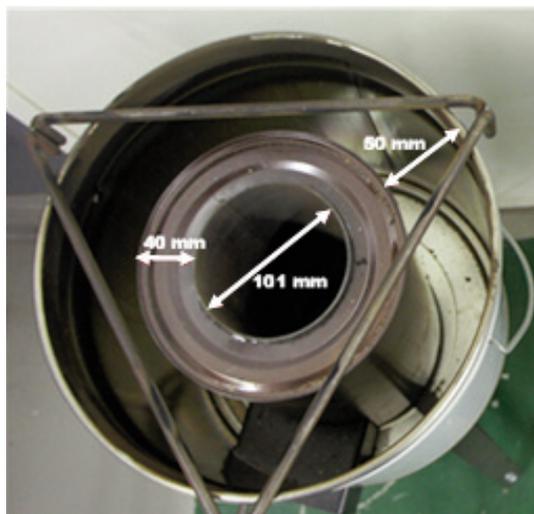


Figure 2: Top view of the combustion chamber layout and dimensions of the biomass stove with a small fuel hopper.

Six variants of the biomass stove were designed and subsequently constructed. These stoves differed in respect with height and diameter of the primary combustion chamber; size and number of secondary air inlets; and the vertical height of the outer metal drum. For each of these, there were three configurations of secondary air inlets (one with no secondary air, one with two vertical inlets, and the last with three inlets created by punching an inward facing flange remaining at a 45° angle to the body. The flanges were punched inwards to induce a vortex in the combustion chamber during normal stove operation. The characteristics of the stoves used are listed in Table 2.

Table 2: The six variants of the stoves designed and used in the experiments.

<i>Large hopper stoves</i>	<i>Abbreviation</i>
Large hopper, no secondary air inlets	LHNV
Large hopper, 2 secondary air inlets	LH2V
Large hopper, 3 secondary air inlets	LH3V
<i>Small hopper stoves</i>	
Small hopper, no secondary air inlets	SHNV
Small hopper, 2 secondary air inlets	SH2V
Small hopper, 3 secondary air inlets	SH3V

The heterogeneous stove testing protocol

A heterogeneous stove testing protocol (HTP) was employed; that is, a collection of tests and methods describing the procedures for thermal efficiency, particle and gaseous emissions performance, fire-power, and fuel-burn rate. The SeTAR Centre, University of Johannesburg [6] provided the HTP facility.

Thermal performance evaluation

Thermal efficiency (μ) was calculated using Equation 1.

$$\mu = \frac{C_p M_w (\Delta T)}{M_f (\text{LHV}_f) - M_c (\text{LHV}_c)} \quad (1)$$

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 in °C, M_f is the mass of the raw fuel burned, M_c 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 there are no evaporative losses; if there are, their effect on the final thermal efficiency numbers are regarded as negligible.

Firepower evaluation

The test procedure used to determine the power settings was adopted from Prasad [31], but with minor changes. Firepower is regarded as synonymous with the burn rate in this case [32]. The stove was filled with fuel, and the mass of the stove and fuel was measured, using a mass balance which recorded the mass loss resulting from fuel consumption per unit of time. The instantaneous power output of the stove was calculated as the mass loss rate multiplied by the lower heating value of the fuel, assuming complete combustion (and that incomplete combustion was negligible), as in Equation 2.

$$P = \frac{(\text{LHV} \times \Delta m)}{\Delta t} \quad (2)$$

where P is the firepower of the stove at a specified power setting, Δt is the time interval, Δm is the mass loss in a specified time interval, and LHV is the lower heating value of the fuel.

Moisture content determination

Each batch of fuel was tested for moisture content (MC) before each combustion test. The MC was determined from the batches of fuel as received from the field. A small sample (~150 g) of the black wattle was weighed on a calibrated scale with 0.1 g accuracy. The sample was then oven-dried at 100 °C for 24 hours, to determine the MC in the fuel. During this time, the sample was weighed occasionally, with this exercise repeated every three hours until the wood had attained dry mass – confirmed by a steady weight without further decrease. The moisture content was calculated on a wet basis using Equation 3.

$$\text{MC}_{\text{wet}} = \frac{MF_{\text{wet}} - MF_{\text{dry}}}{MF_{\text{wet}}} \times 100 \quad (3)$$

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

Pollutant emissions determination

A testing protocol was conducted by means of a carbon balance method to calculate the net gaseous pollutants per megajoule (MJ) of the net heat gained by the cooking vessel. By measuring the concentration of each carbon-containing compound in the exhaust (CO_2 , CO, HC), it is possible to balance the sum of the emissions against the stove's fuel-burn rate. The method assumes that all carbon in the fuel is converted to a known carbon pollutant. A modification of the hood method [33] was used for evaluating emissions. Since the experimental stoves did not have a flue, the stoves were placed under a collection hood attached to the dilution system, which was responsible for the ducting and dilution of the exhaust gas stream (Figure 3). Since a high extraction rate may influence the combustion characteristics of the stove [32], an extractor fan was not used for drawing air through the hood and duct. The hood method can be used simultaneously with a method for determining thermal parameters. This has the added advantage of enabling simultaneous measurements of emissions and thermal parameters in a systematic and standard manner [34].

The gas analysis was carried out on a sample taken directly from the flue and passing through a filter. Another sample was drawn from the flue and diluted with a known volume of high-efficiency particulate air (HEPA)-filtered compressed air. The sampling configuration of the undiluted flue gas channel included, in sequence, a stainless-steel channel, a filter holder and a flue gas analyser (Testo® 350XL/454). The sampling configuration for the diluted channel included, in sequence, the dilution system, a Teflon tube channel; and a flow splitter to take gas samples to the TSI DustTrak 8533 aerosol monitor and a second Testo flue gas analyser. The Testo measures CO_2 , CO, NO_x , NO_2 , H_2 , H_2S , S, SO_2 and O_2 . The DustTrak DRX Model 8533 is a desktop instrument that simultaneously measures size-segregated mass fraction concentrations (PM1, PM2.5, PM4, PM10, and total particle mass) in real time over a wide concentration range of 0.001–150 mg/m^3 .

Emission factors

Emission factors presented in this study were calculated as in Bhattacharya [33] with slight modifications (no methane and non-methane hydrocarbons measurements) and for energy-specific emission factors in units of energy in the fuel (g/MJ) [6]. Concentrations of CO, CO_2 and NO_x (ppmv) were recorded in each test every 10 seconds for the duration of the burn sequence or the test experiment. Equations 4 and 5 give energy-specific emission factors for CO_2 and CO expressed in g/MJ.

$$\text{CO}_2\text{EF} = \eta \text{CO}_2 \times M_{\text{CO}_2} (\text{net heat gained})_{-1} \quad (4)$$

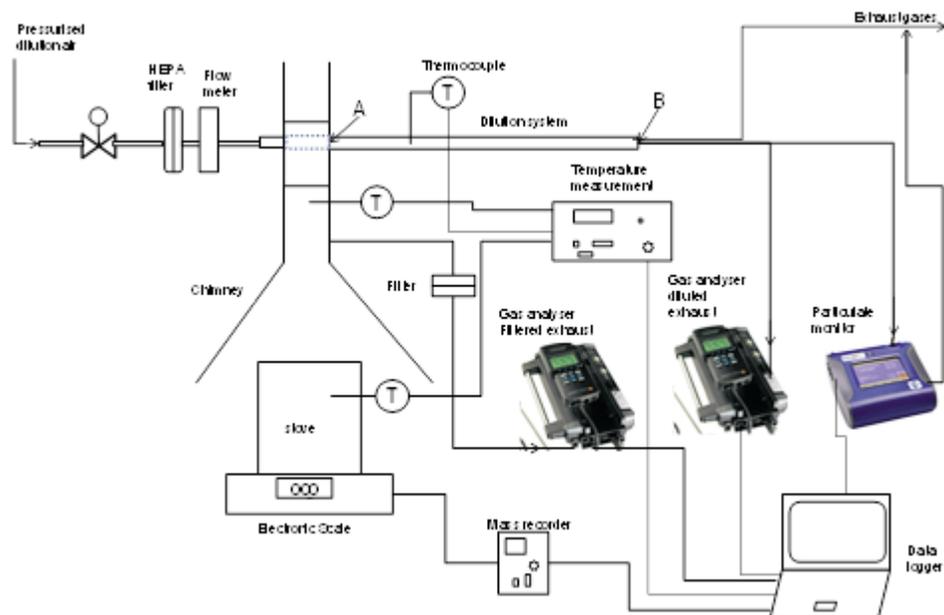


Figure 3: Schematic illustration of the experimental dilution set-up for the SeTAR dilution systems, showing the mixing point (A), the sampling point (B), and thermocouples (T).

$$\text{COEF} = \eta_{\text{CO}} \times M_{\text{CO}} (\text{net heat gained})^{-1} \quad (5)$$

where the net heat gained refers to the heat retained by a cooking vessel during the water heating experiments, EF is emission factor, and M is the molecular mass of the pollutant.

The standard reporting metrics for the particle mass (PM) concentration include the mass of PM emitted per net megajoule of energy (HNET) delivered into the pot, or mass of PM emitted per net megajoule of energy delivered from the fire [6]. The metric mass per net megajoule of energy delivered into the pot was used for all emission factor calculations. For example, the mass of $\text{PM}_{2.5}$ emitted during a burn sequence is determined using Equation 6.

$$\text{PM}_{2.5}\text{EF} = \frac{\text{PM}_{2.5}(\text{g})}{\text{HNET}(\text{MJ})} \quad (6)$$

Performance-based ranking of stoves

The criterion used for ranking stoves was based on the rank score method [35], whereby equal weight was given to each of the parameters under investigation. The stove with the best performance per given parameter or task out of the six stoves evaluated received a score of one, while the stove with the worst performance received a rating of six. The stove with the lowest average scores for all the parameters combined was ranked best. For an example, assume the CO/CO_2 ratios for six stoves (A–F): stove A (1.5%), stove B (5%), stove C (2.5%), stove D (4%), stove E (3%) and stove F (2%). Stove A would attain 1 point, stove F 2 points, stove C 3 points, stove E 4 points, stove D 5 points and stove B 6 points. Stove A would be best performer in context with combustion efficiency.

Quality control

For each fuel/stove combination, a series of preliminary burn sequences was carried out to standardise procedures and to minimise the variability from differences in user/operator behaviour. Thereafter, five definitive tests were conducted for each fuel stove/combination. After every test run, the gas probes and Teflon tube channels were cleaned; and the pumps and machines checked and zeroed [6].

Continuous gas and particle monitoring instruments were routinely sent for calibration at intervals prescribed by the manufacturers, or at least once annually, and needed to be periodically verified with laboratory standards. Zero and span calibration were performed on all analysers before and after every test run to account for small variations in the dilution ratio. For example, the DustTrak DRX was zeroed with filtered air before each test run [6].

The sampling dilution system components were disassembled before conducting test experiments, cleaned, air-dried, and re-assembled. High power compressed air and water were used to remove large particles from the sampling channels. The exhaust collection trains, involving stainless steel ducts, Teflon tubes and sampling nozzles, were cleaned with soap and water and air-dried with filtered compressed air [6].

3 Results and discussion

3.1 Thermal efficiency

A summary of the thermal performance results is given in Table 3. The results showed that the biomass stoves with a large fuel hopper performed better than those with small fuel hoppers for time to boil, heat flux, and firepower. Thermal efficiencies of the biomass stoves were estimated between 20% and 30%, with the specific fuel consumption rang-

Table 3: Thermal performance results of the experimental wood-burning cookstoves.

Stove type	Time to boil 1 litre of water	Burn rate (g/min)	Specific fuel consumption (g/min/litre)	Heat flux (W/cm ²)	Firepower (kW)	Thermal efficiency
<i>Large hopper</i>						
LHNV	5.8 ± 0.1	16.4 ± 0.8	3.3 ± 0.2	1.8 ± 0.5	3.5 ± 0.6	24.3 ± 1.3
LH2V	4.3 ± 0.5	18.8 ± 3.8	3.8 ± 0.8	2.4 ± 0.2	4.2 ± 0.3	26.5 ± 3.7
LH3V	6.8 ± 0.8	16.2 ± 4.1	3.2 ± 0.8	1.6 ± 0.2	3.5 ± 0.5	26.6 ± 5.5
<i>Small hopper</i>						
SH3V	7.2 ± 0.8	8.5 ± 2.5	1.7 ± 0.5	1.5 ± 0.2	2.1 ± 0.7	31.8 ± 2.2
SH2V	7.5 ± 0.5	10.4 ± 1.9	2.1 ± 0.4	1.5 ± 0.3	2.5 ± 0.5	23.8 ± 2.1
SHNV	8.5 ± 0.9	12.0 ± 1.7	2.4 ± 0.3	1.1 ± 0.3	2.9 ± 0.5	33.6 ± 6.9

LHNV= large hopper, no secondary air inlets; LH2V = large hopper, 2 secondary air inlets; LH3V = large hopper, 3 secondary air inlets; SHNV= small hopper, no secondary air inlets; SH2V = small hopper, 2 secondary air inlets; SH3V = small hopper, 3 secondary air inlets.

ing from 9 to 30 g/L water boiled (Table 3). The stoves large fuel hoppers recorded lower thermal efficiencies than those with small fuel hoppers. The large hopper stoves gave an average thermal efficiency of 22% ± 2%, while the small hopper stoves had an average thermal efficiency of 28% ± 2%. There was an inverse relationship between thermal efficiency and the height of the combustion chamber. These differences are attributed to heat absorption along the length of the combustion chamber. Taller flue heights were likely to be less energy efficient because of the significantly greater distance between the pot and the radiant heat of the burning wood, although Table 3 shows that taller flue heights produced less particulate matter. Shorter flue heights produced more smoke but had higher heat transfer efficiencies because of the proximity of the cooking vessel to the radiant heat of the burning wood.

3.2 Firepower

Table 3 shows that the firepower of the stoves with large fuel hoppers was found to be between 3.5 and 4.2 kW in comparison with between 2.1 and 2.9 kW for the small hopper stoves. The firepower in the large hopper stoves was found to be up to 31% greater than in the small hopper stoves, across the

entire combustion sequence. This increase in firepower was caused by an increase in the burn rate of fuelwood, which is influenced by the stove ventilation rates and the size and height of the combustion chamber.

The firepower profile for the experimental cookstoves across the entire combustion sequence is shown in Figure 4. The temperature of the combustion chamber during the ignition phase gradually increased with an increase in the temperature of materials used for constructing the fuel hopper of the cookstoves [27]. The large hopper stoves, for an example, experienced a firepower increase to 8 kW (LH2V) at ignition, followed by stabilising to about 4 kW.

3.3 Fuel consumption

Table 3 shows that the large hopper stoves recorded a higher burn rate than the small hopper stoves. Ventilation rates based on the number and size of secondary air holes affected the performance of the stoves, those with single and three secondary air inlets having higher specific fuel consumption rates. The LHNV had a specific fuel consumption rate of 30 g/L litre water boiled, while the SHNV stove had a specific fuel consumption rate three times less. The stoves with two secondary air inlets, LH2V and

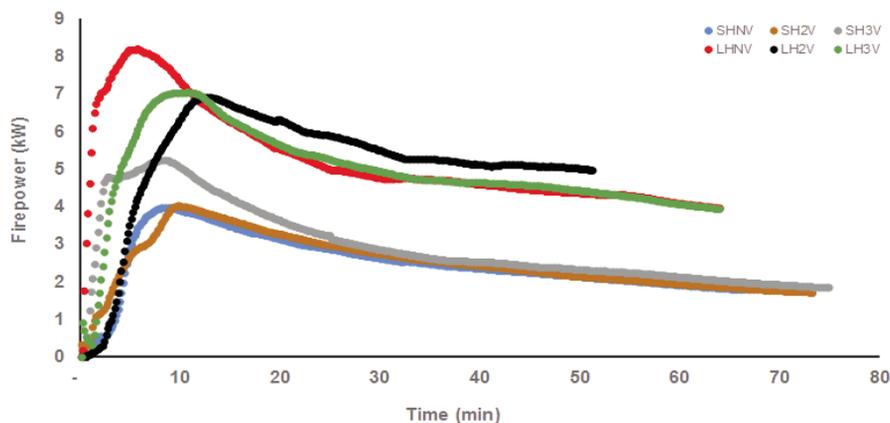


Figure 4: The firepower profile for all experimental stoves across the entire burn sequence in kW.

SH2V, recorded the most efficient fuel consumption rates of 13 and 9 g/L respectively.

3.4 Heat flux

Table 3 shows that large hopper stoves registered better heat flux than the smaller hopper stoves. Stove science defines heat flux as a rate of energy transfer through the base of a cooking vessel per unit time. Current stove programmes, especially those spearheaded by the World Bank, have set heat flux requirements for improved cookstoves to 2 W/cm², where W is essentially 1 Joule/second [36]. Any stove that does not meet this requirement is not regarded as a significant improvement to some of the known benchmarks. Only the LH2V stove met these requirements, while the small hopper stoves averaged 1.5 W/cm².

3.5 Time to boil

Table 3 also presents the average boiling times of a pot filled with 5 000 g of water for the cookstoves tested. The specific times to boil a litre of water were also computed for all the experimental stoves. Boiling time was determined using a high-power boiling test with the pot cover/lid. It was found that large hopper cookstoves experienced lower specific boiling times than small hopper cookstoves, because they have a higher fuel burn rate and increased average firepower. The improved firepower increases the stoves' ability to transfer heat energy from the fuel to the cooking vessel.

3.6 Ranking of stoves based on thermal performance

The experimental stoves can be ranked from best to worst using the thermal performance results presented in Table 3. The criteria considered the time to boil, fuel consumption rate, heat flux, firepower and thermal efficiency. The thermal performance in this study followed the order LH2V > LHNV > LH3V = SH3V > SHNV > SH2V.

3.7 Emissions performance

The results from emissions monitoring equipment during performance testing of the experimental stoves involve mass and energy specific emission factors determined over five complete runs of the HTP water-heating test. A summary of the pollutant emissions results is presented in Table 4.

Moving averages of pollutant concentrations over all five complete runs of the HTP water heating test were determined. Plots of PM_{2.5}, CO, and the CO/CO₂ ratio are illustrated in Figures 5–7. Poor combustion conditions in all the experimental stoves tested were experienced during the ignition phase and the smouldering stage.

The present study postulates that fuel-bed temperatures influence particle formation during the ignition and smouldering periods of wood-burning. The ignition stage involves the devolatilisation of wood upon heating, resulting in the release of semi-volatile organic compounds (SVOCs). These gases are low in free oxygen and cool rapidly when passing through the fuel hopper above the combustion zone. Under these conditions, much of the evolved SVOCs escape before combusting and condense to form the dense white smoke characteristic of the ignition phase of natural draft wood-burning stoves. When visible flames begin to emerge above the fuel bed, the PM emissions start to drop significantly. Fuel-bed temperatures will increase rapidly as the volatile matter is combusted until there is insufficient volatile matter evolving from the burning wood macromolecules to sustain this homogeneous gas-phase combustion. This is essentially an exothermic heating state following the endothermic moisture removal as vapour, so that the volatile matter act as oxygen to accelerate the attainment of combustion. This phase progresses until the char formation phase occurs, which results in good combustion efficiency. During this phase, heterogeneous gas/solid combustion takes place, with the rate limited by C* active sites for further gasification

Table 4: Emissions performance results of the experimental wood-burning cookstoves.

Stove type	CO (g/MJ)	CO (g/hr)	CO (g/kg)	CO/CO ₂ (%)	PM _{2.5} (g)	PM _{2.5} (g/MJ)	PM _{2.5} (g/hr)	PM _{2.5} (g/kg)
Large hopper								
LHNV	1.5 ± 0.4	20.3 ± 0.7	23.3 ± 5.8	2.2 ± 0.4	0.017 ± 0.005	24.0 ± 8.9	0.0003 ± 0.0001	0.02 ± 0.03
LH2V	0.9 ± 0.1	14.4 ± 2.9	13.9 ± 1.8	1.5 ± 0.2	0.012 ± 0.004	5.3 ± 3.4	0.0002 ± 0.0001	0.01 ± 0.005
LH3V	1.2 ± 0.4	14.5 ± 2.3	18.7 ± 6.5	2.0 ± 0.7	0.020 ± 0.002	14.6 ± 1.0	0.0003 ± 0.00004	0.02 ± 0.008
Small hopper								
SH3V	1.5 ± 0.3	14.9 ± 1.1	23.9 ± 6.6	3.0 ± 1.3	0.026 ± 0.01	30.1 ± 9.2	0.0004 ± 0.0002	0.05 ± 0.04
SH2V	2.8 ± 0.2	26.0 ± 7.0	45.8 ± 9.5	4.9 ± 0.6	0.061 ± 0.02	113.5 ± 9.9	0.0010 ± 0.0003	0.10 ± 0.05
SHNV	1.6 ± 0.4	13.5 ± 4.2	27.6 ± 3.1	3.0 ± 0.3	0.054 ± 0.02	77.3 ± 9.7	0.0009 ± 0.0003	0.08 ± 0.01

LHNV= large hopper, no secondary air inlets; LH2V = large hopper, 2 secondary air inlets; LH3V = large hopper, 3 secondary air inlets; SHNV= small hopper, no secondary air inlets; SH2V = small hopper, 2 secondary air inlets; SH3V = small hopper, 3 secondary air inlets, g/MJ emission factors are given based on MJ of energy transferred to the pot.

with CO₂ [37]. The product of the surface reactions is CO-rich, which undergoes further combustion in the gas phase to CO₂ [6].

The PM_{2.5} emissions, however, begin to increase towards the end of the char-formation stage and nearing fuel burnout (~60 min), ascribed to the gradually reducing depth of the fuel bed and lowering temperatures.

An increasing trend in CO concentration can be observed for all experimental stoves through the progression of the test runs (Figure 6), which confirms both the gasification and combustion reactions taking place in competition. The peaks in CO at the end of the combustion sequence could also be attributed to the build-up of ash around the fuel matrix. During this stage of combustion (i.e. smouldering), oxygen becomes the limiting factor. The ash layer acts like insulation, reducing heat transfer from the char and slowing the overall reaction. Hence, CO gas is produced by a gasification process because of partial oxidation of the char surface

[37]. As the surface temperature of the char rises, reactions forming CO exceed those forming CO₂. This reduced combustion efficiencies and increased emissions CO gas [38]. The CO₂ gas dissociates into CO and O. The O adsorbs onto the char matrix transforming the solid C to gaseous CO [37]. The high CO concentrations in the smouldering phase indicate a need for further design considerations to lower the CO emissions as this high emission rate has the potential to contribute to air pollution.

The combustion efficiency measured as a function of the ratio of CO to CO₂ was estimated (Figure 7). Results showed that the large hopper stove with two secondary air inlets (LH2V) had a ratio of 1.5%, which falls within the South African National Standards specifications for non-pressurised liquid paraffin fuelled stoves (SANS 1906:2009). Currently there are no national standards for wood-burning cookstoves in South Africa. Comparing the CO/CO₂ ratio with standards in other countries, all the experimental cookstoves except for the small

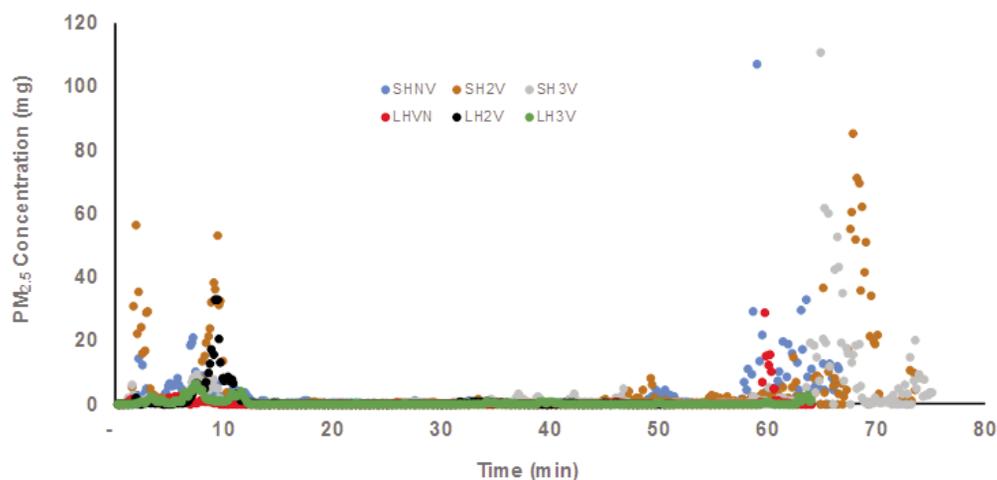


Figure 5: Average PM_{2.5} (mg) emissions of the experimental stoves over five complete heterogeneous stove testing protocol water heating test runs.

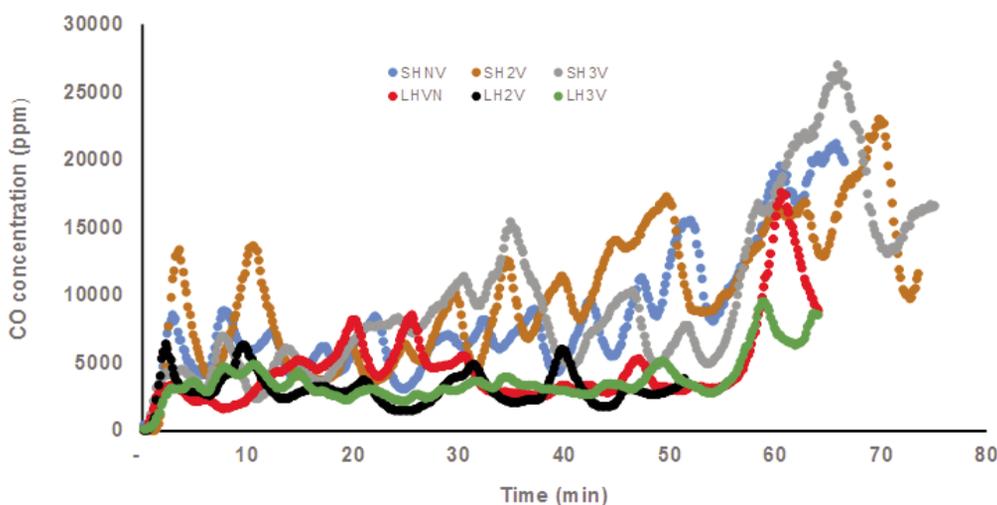


Figure 6: Average CO (ppm) emissions of the experimental stoves over five complete heterogeneous stove testing protocol water heating test runs.

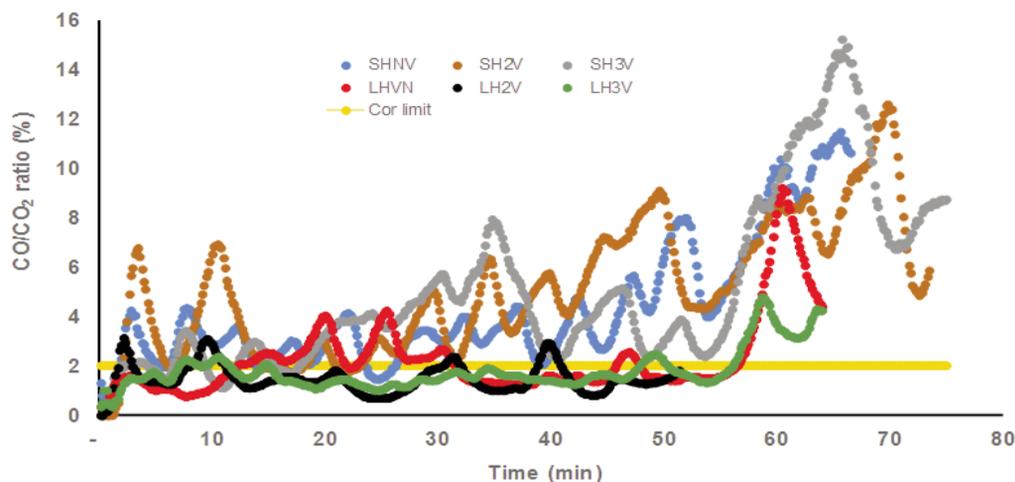


Figure 7: Average CO/CO₂ ratios (%) of the experimental stoves over five complete HTP water heating test runs. The yellow line indicates the SANS 1906:2009 limit standard for CO/CO₂ ratio in non-pressurised paraffin stoves.

hopper cookstove with two secondary air inlets (SH2V) failed to comply with the Bureau of Indian Standards requirement of 4% limit on the CO/CO₂ ratio [39].

3.8 Ranking of stoves based on emissions performance

The experimental stoves ranked from best to worst using the emission performance results provided in the order LH2V > LH3V > LHNV > SH3V > SHNV > SH2V, as presented in Table 4.

4 Conclusions

Six wood-burning stoves were designed, developed and tested for thermal and emissions performance using the heterogeneous stove testing protocol. It was found that each stove type had some specific quality over other stove types. The large hopper stove with two secondary air inlets ranked higher and exhibited better performance regarding thermal and emissions parameters than the others. The large hopper stoves outperformed the small hopper stoves although the latter recorded higher thermal efficiency values. Fuel consumption rates were higher in large hopper stoves than in small hopper stoves, giving increased firepower. Again, large hopper stoves outclassed small hopper stoves regarding emissions performance. The large hopper designs were, therefore, ideal candidates for further research. The experimental work presented herein shows the need for iterative designing and testing of cookstoves for emissions and thermal performance to identify a candidate stove for dissemination.

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