

A wood gasification stove for domestic use: Performance and emission factors using locally available fuel.

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Abstract

It has been shown that large numbers of low-income SA households use wood for domestic cooking and space-heating purposes and are exposed to high concentrations of air pollutants emitted from the unsophisticated appliances being utilised. Although the related problem of exposure to coal smoke from domestic fires has been and is being addressed, wood smoke exposure remains a pressing problem. The design of a more efficient wood using appliance therefore has the potential to reduce the particulate matter exposure of a considerable portion of the SA population. This paper presents the results of testing a natural draft wood gasification stove for domestic use based on the inverted downdraft principle. Prototypes have been built in two sizes, suitable for relatively unsophisticated manufacturing techniques. The results of performance and emission factor testing using a laboratory fuel as well as fuel obtained from the local programme for eradication of invasive tree species (known as Working for Water) are presented. It is shown that simple wood gasification stoves can result in a considerable reduction in exposure of household members to particulate matter inhalation.

Keywords: domestic energy supply, inverted downdraft wood gasification, wood stove emission factors

1. Introduction

The largest contribution to air pollution in dense, low-income communities in South Africa is caused by the use of wood and coal in urban areas on the Highveld and use of wood in rural areas for space heating and cooking, although electricity and paraffin are preferred by many of the same households for cooking. Coal use is the most significant contributor to health impacts from air pollution in the urban areas (FRIDGE 2004). However, the majority of wood users (about 95% of wood users or 2.47 million households) live in rural areas.

Data on the use of wood and other biomass in both rural and urban households has attracted considerable interest in the research literature (e.g. Kimemia *et al* 2011, Adkins *et al* 2012); in addition to the extensive use of wood in rural areas, it has been shown that there is considerable use of wood even in urban areas (Kimemia & Annegarn 2011). The choice of energy carrier is not only determined by availability (about 80% of households have access to electricity) but also by the absolute cost and cost-efficiency of appliance systems (Friedl *et al.* 2008, 2009). It has however been shown that the particulate matter (PM) emission factors for the use of wood, whether calculated per kg of fuels used or per unit energy delivered is considerably higher than for coal (FRIDGE 2004). This paper reports on the development and testing of a natural draft wood gasification stove for domestic use to reduce this emission factor. Although pine wood cubes were initially used for the development and testing in order to provide a standard and reproducible fuel, testing was also carried out with biomass produced by the SA Department of Environmental Affairs' "Working for

Water" (WfW) programme (Department of Environmental Affairs 2013). This is a programme that has the eradication of alien invasive vegetation as its objective and which has cleared a million hectare of such species since its inception in 1995. It has also produced 20 000 jobs since that year. In this study, black wattle (*acacia mearnsii*) cleared near Magaliesburg in Gauteng was used, which renders it unsuitable for cooking purposes. For a wood gas stove to work using only natural convection, it needs to be an inverted downdraft gasifier which is ignited at the top. The primary air enters at the bottom and moves up through the packed bed of fuel with a draft of approximately 100µm water pressure due to the buoyancy of the 500°C pyrolysis gas (Reed & Larson, 1996). Secondary air is then allowed to mix with the wood gas to prepare the fuel/air mixture necessary for combustion. Initial dimensions were 17 cm diameter with each of the sections being 15 cm high. This was scaled up to a "meal preparation" size with an outer diameter of 22 cm with the bottom section being 30 cm high and the top section 450 cm high.

2. Methodology

2.1 History of wood gasification

Gasification of wood and coal was known and used since 1800, with major applications of coal-based "gaslight" in London and Paris during the 1850s. The first large scale application of wood gas generators occurred during World War II when petroleum shortages forced road transport users in Western Europe to find alternative fuels for their

vehicles. These 5-100kW gasifiers were of the conventional downdraft type where air is forced down through the packed bed of fuel. The volatiles and tars are burnt while charcoal and wood gas are made. (Reed *et al.*, 2000; Reed & Larson, 1996).

If a packed volume of fuel is ignited from the bottom, it is referred to as an updraft gasifier. The biggest drawback of updraft gasification is the large amount of tar produced while consuming the charcoal residue, which renders it unsuitable for cooking purposes. For a wood gas stove to work using only natural convection, it needs to be an inverted downdraft gasifier which is ignited at the top. The primary air enters at the bottom and moves up through the packed bed of fuel with a draft of approximately 100µm water pressure due to the buoyancy of the 500°C pyrolysis gas (Reed & Larson, 1996). Secondary air is then allowed to mix with the wood gas to prepare the fuel/air mixture necessary for combustion.

2.2 Design

The design of two types of inverted natural downdraft wood gasifiers based on work by Anderson and Reed (2004) and an existing forced draft camping stove design was described earlier (Kornelius *et al.* 2012). The aim was to be able to boil a litre of water in ten minutes, thus allowing cooking on limited scale. In the “double volume” version selected for further development (see figure 1 below), gasification takes place in the bottom section while mixing of the gas with secondary air and combustion takes place in the top section. Initial dimensions were 17 cm diameter with each of the sections being 15 cm high. This was scaled up to a “meal preparation” size with an outer diameter of 22 cm with the bottom section being 30 cm high and the top section 450 cm high.

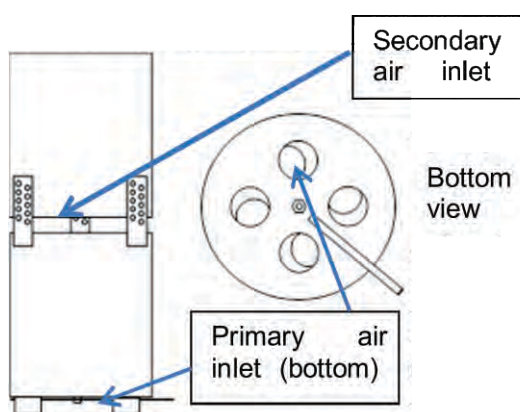


Figure 1: “Double volume stove”; gasification in the lower section, combustion of gas in the upper.

The use of an outer sleeve made of light galvanised sheet around the lower (gasification) section of the scaled-up “double volume” model showed some promise with regards to protection against injuries

and the pre-heating of combustion air, but needs development and was not tested further. The larger version was also tested with a perforated 25 mm dia metal tube inserted vertically on the centre line of the gasification section to improve air distribution; this was in fact found to reduce the performance as it hinders the even movement of the gasification zone through the fuel bed.

2.3 Fuels

The three types of fuel initially tested were industrial wood waste (wood shavings), pine wood cubes and sickle bush firewood chopped to the desired dimensions as proposed by Anderson & Reed (2004). For tinder a small amount of ethanol gel was initially used as this does not drip and promotes quick lateral distribution of the fire on the fuel bed surface. Due to the limited availability of ethanol gel in informal settlements, subsequent tests using newspaper layers over the top of the wood bed showed that this also provides suitable tinder.

It was soon found that the industrial wood shavings did not allow for sufficient bed porosity and had too high a moisture content to allow consistent gasification without forced draught. To ensure reproducible fuel properties, initial development work was therefore done with approximately uniform pine wood cubes with 1 cm sides providing a bulk density of approximately 180 kg/m³.

The WFW black wattle consisted of branches with varying diameters up to 3 cm; these were cut into lengths of approximately 1 cm for testing. It was found that drying to a moisture content of approximately 7% was required for the gasifier to operate satisfactorily on this fuel; this could be achieved by protecting the wood against rain and drying in the sun on clear days. Bulk density was 470 kg/m³ as used.

3. Testing

3.1 Performance

Practical energy output was measured by plotting the temperature change and/or evaporation rate of water in a suitably sized container being heated on the stove. Emissions factors were determined by operating the stove under a hood with a chimney and using flow measurement through the chimney by vane anemometer, with a stack gas test apparatus (IMR 2000, IMR Ingenieurgesellschaft für Mess- und Regeltechnik mbH) for gas concentration measurements and a laser particle counter (Sidepak AM510, TSI Inc.) with a 10 µm impactor used for particle concentration measurement. The total amount of the pollutants could be determined in this way and normalised to the fuel mass used and the energy output.

In each case, primary and secondary air supply openings to provide the highest rate of heating combined with a visibly clean flame were used. It was found that the black wattle required a smaller secondary air opening (relative to the pine cubes) to operate without visible particulate emissions.

Practical output values for batch operation of the smaller stove (typically 15 minutes) are given in table 1 below.

Table 1: Small-scale stove practical output.

Type	Output (kw)
FD camping stove	1.18
Double volume (pine)	1.02
Double volume (black wattle)	1.11

All of these stoves are capable of boiling a litre of water in less than 10 minutes in a batch mode. The intermittent feeding of additional wood cubes has been tested and has shown the potential to considerably extend operational time without causing upsets in operational conditions. Preliminary testing of CO and NO_x concentrations indicated that the natural draught produced considerably higher CO and NO_x concentrations than the forced draught prototype, indicating inferior gasification and mixing of gas and secondary air compared to the forced draft model.

3.2 Performance (upscaled)

Initial performance results at the optimum settings of the larger-scale stove with the pine cube fuel, determined from the temperature vs. time curves of a 4L container of water are given in figure 2 below. The break in the curves indicates the time where the water was boiling and the container was replaced by one containing water at room temperature. Maximum output was 3 kW (measured from the slope of the curves) and the average output over the entire 77 min combustion period was 2.2 kW using a single batch (10l or approximately 1.8kg) of pine cubes.

With a similar mass of black wattle and with the centre tube in place, average power was 0.7 kW for a period of 31 minutes; with the centre tube removed, 1.07 kW was achieved for 18 minutes. However, as shown in figure 2, firing times of 80 minutes can be achieved with a single fuel charge.

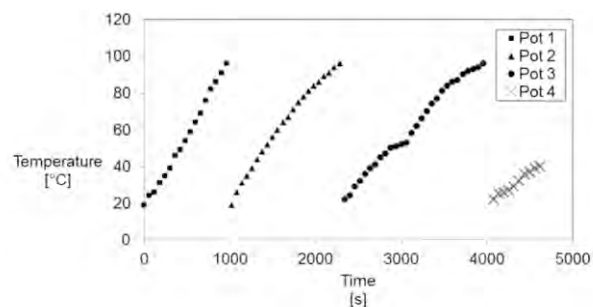


Figure 2: Temperature history for upscaled double volume stove using pine.

3.3 Emission factors

Emission factors were obtained for the optimum run with pine, and for the optimum run with the centre tube using black wattle of the upscaled stove as in table 2 below. The figures in the last column are the comparative ones given in (FRIDGE 2004).

Table 2: Small-scale stove practical output.

Pollutant	g/kg of wood used		
	Gasification (Black wattle)	Gasification (pine)	Open fire
SO ₂	0.135	<0.78	0.18
NO _x	0.67	0.23	5
PM ₁₀	0.433	0.04	15.7
CO	17.3	0.16	114.6

4. Conclusions

An inverted natural downdraft wood gasification stove that has the potential to be built using readily available local materials has been designed and tested at approximately 1 kW practical output levels. This is sufficient for most cooking purposes, while the larger unit has the potential to be used for space heating.

Operation is robust, with the potential for intermittent feeding to extend operating times.

Although the output was lower and the emission factors higher using mixed size locally black wattle wood chips, this still represents a considerable improvement (97.5% in the case of PM₁₀) over the emission factors for open fires. The simplicity of the design also offers good possibilities for rural manufacture.

5. Acknowledgements

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