Abstract

A growing interest in accurately specifying domestic cooking and heating stove performance stems from increasing concern for women and children exposed to unhealthy levels of gaseous and particulate emissions, and for certifying and rating stove-fuel combinations for the mitigation of greenhouse gases. Popular flame-based stove testing protocols show inadequacies in the outputs as they do not represent real-world uses or likely combinations of fuels, stoves, and pots. The Sustainable Energy Technology Testing and Research Centre (SeTAR Centre), University of Johannesburg is developing heterogeneous emissions and thermal performance protocols for a range of stoves and fuels including paraffin, ethanol, wood, charcoal and bituminous coal - all fuels in widespread use in Southern Africa. The new protocol requires each appliance to perform realistic tasks (boiling water in two litre and six litre pots) at three different power levels; and that stoves be tested using the range of fuels and pots for which they were designed. The composition and heat content of each fuel used must be routinely determined. We present sample test results illustrating how we obtain insightful design information and robust evaluations. These protocols will be published, providing improved practices for stove development, efficiency rating and product certification.

1. Measuring Stove Performance

Project managers and funding agencies often select a stove type by reviewing laboratory test results, especially comparative tests of a range of stove designs. The numbers reported by such comparisons are therefore important to stove developers who want to sell products or design services, or have stoves introduced as part of development aid or climate protection initiatives.

When industrial equipment is rated for performance there are standard approaches taken to the testing and standard formats for the outputs. Heating appliances are usually rated by calculating work done per unit of heat used. Combustion might be ‘emissions per unit of heat produced’ or ‘per kilogram of fuel burned’. Using these metrics the efficiency or emissions or fuel used to perform any given task can be estimated, with laboratory or field tests conducted for confirmation. Efficiencies of various parts of the combustion and heat transfer processes may be used to calculate an overall task performance. However, tasks, being combinations of efficiencies, cannot be deconstructed to reveal the underlying efficiency numbers.

To date, standard performance figures for improved stoves have not been readily available, because the Improved Cooking Stove sector has not had an agreed set of testing criteria and protocols, devised under the guidance of a professional standards setting agency. Many developers feel historically constrained to conduct all testing in terms of a standardised task. This presentation will present a set of heterogeneous testing protocols for emissions and thermal performance from domestic cooking stoves, developed as part of a South African stove testing programme. Through presentation and discussion of representative results, we illustrate how a heterogeneous set of tests can provide essential information for the rating, comparison and ranking of a stove’s performance. By implication, we illustrate why task-based evaluations, often used heretofore, are inadequate for performance evaluation of domestic and institutional flame-based cooking devices.

2. Compulsory Stove Standards

The American Environmental Protection Agency (US-EPA) provides a number of methods for testing heating and cooking appliances. Their compulsory certification test for free standing space-heating wood stoves is typical of early efforts to produce a compulsory national standard testing procedure. It prescribes the fuel, its method of use, the test conditions and the method of operating the stove. However, it has proven to be controversial, disappointing testers and manufacturers alike.

The South African (SA) government has passed compulsory paraffin stove performance and safety standards, prepared by the SA Bureau of Standards (SABS). It allows new products to be operated in new ways, but still prescribes the fuel and the test conditions which include among other things, a full power burn under a hood to test the CO/CO₂ ratio as the core test.

New Zealand has regulations that permit any stove and most fuels to be operated according to the manufacturer’s recommendations, as long as they meet certain emission and durability standards. This has permitted clean-burning wood pellet space-heating stoves to enter a market where previously all wood fuel had been banned. The New Zealand technical advisors realised that the fuel alone is not the cause of air pollution, but that the stove/fuel combination need to be optimised.

New test protocols are required to deal with this more realistic approach to testing and certification of cooking stoves.

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3. STANDARD METRICS – SETAR CENTRE ACTIVITIES

As part of a national project to develop safer, cleaner burning and more energy efficient domestic flame stoves to replace the ubiquitous and highly polluting coal braziers, South Africa is engaged in assisting industry to design and evaluate new ethanol gel and paraffin stoves. The recently formed Sustainable Energy Technology Testing and Research (SeTAR) Centre at the University of Johannesburg was commissioned to determine the thermal efficiency and gaseous emissions of several stoves, including new prototypes or products recently made available on the market. (Our competence excludes testing of product safety, which is properly the domain of the South African Bureau of Standards.)

Eight different designs were provided for testing. In the process of evaluating these stoves for thermal and emissions performance, SeTAR staff was engaged simultaneously in the development of written procedures for testing and development of spreadsheet calculations that included both primary and secondary combustion effects. Importantly, these calculations take into account fuel moisture and oxygen content of the fuel. The protocols required operation of the devices at a range of power levels, using two different pot sizes.

The sections that follow illustrate some of the aspects of the test protocols and results from the more than one hundred individual tests conducted as part of this project.

4. TEST RESULTS – BASELINE PARAFFIN WICK STOVE

Figure 1 shows the carbon monoxide emissions factor, CO(EF) (Lambda corrected for Excess Air), from a paraffin wick stove, from ignition of the fuel through a boiling episode, and includes tests at three different power levels with the pot in place.

This stove has a CO level that increases with time on High, drops with time on Low, and stabilises on Medium power. It also indicates that on Low there is a significant variation in the combustion efficiency, the result of a wavering flame. The data used to generate charts, such as shown Figure 1, can be used to make direct comparisons with other stoves, provided the CO values are corrected for Excess Air. Together with the measurements of the CO₂ emitted and simultaneous measurement of the mass of fuel burned, and considering the elemental composition of the fuel, Figure 2 shows the derived parameters that can be calculated for the different phases of the test.

Figure 1 CO emission profile for a wick type paraffin stove, plotting the carbon monoxide emission factor (emissions corrected for Excess Air) over time (Stove 3, Test 7). Pot size is 6.8 litres. The regions between pairs of similarly coloured vertical lines indicate periods of stable flame at different power settings. The dotted green line (boiling point) is indicated by an arrow.
This profile is typical of the old type of paraffin burning wick stove. The emissions are what we have come to expect, or more correctly, what we usually think is going on in a stove. The turn down ratio is modest, the CO/CO₂ ratio is high, slightly higher when the power is turned up, but quite stable throughout the whole test. Tested in High power alone, it would give a clear indication of the expected performance at any other power setting.

5. NEW TYPE PARAFFIN STOVE

In order to provide safer and cleaner paraffin stoves, many new products are entering the market with numerous novel features. Let us now look at a new type of single-pot portable stove with very low CO emissions when operated at full power. As High power operation is usually the worst case scenario for emissions, the South African Bureau of Standards (SABS) testing protocol requires that the stove be run at this maximum setting, predicting a consistent CO/CO₂ result similar to that observed in Figure 2. However, looking at the test results for this stove (Figure 3), there is obviously a very large variation in the CO(EF) depending on the power setting. A standard water boiling test would not reveal this variation if, for instance, Medium power was required for simmering, a common occurrence. However paraffin stoves are often used on Low power setting for space heating at night and the emissions should be quantified also for this condition.

The initial jumpy nature of the line in the first few minutes is caused by a very high Excess Air ratio. As soon as the fire is well established and the fumes are collecting under the hood, the line stabilises. If the CO₂ is calculated from the Excess Air figure, richer gas samples are required, above 2% CO₂ and preferably above 4%.

The delay between lighting and the beginning of the High power phase (left Red line) is 5 minutes. A similar delay is used for any change in power during which emissions are ignored save when calculating the overall values. Note the interesting drop in the CO(EF) concentration when switching from Medium (orange) to Low (blue) power - this is caused by the mechanical device that changes the fuel burn rate. After the flame stabilises, the combustion efficiency becomes much worse.

The erratic measurements when the stove is on Low are because of an unstable flame, not from the Excess Air being too high, i.e. it is not an instrument error. As can clearly be seen, the CO(EF) rises as the power level of the stove is gradually turned down.

This profile would be missed during a standard water boiling test which does not include testing over a range of power settings. If the test was conducted using a pot with no lid, it is unlikely to maintain a simmer or rolling boil on low power, so the test would miss the dramatic change in performance. For meaningful design feedback (performance and efficiency) the stove must be tested across its full power range. The green lines indicate the emissions starting when the pot was first put on the lit stove until the water boiled.

The hydrogen in the exhaust is also an indicator of incomplete combustion. The H₂(EF) (Figure 4) has a profile very similar to the CO(EF) chart (Figure 3). H₂ is consistently about one sixth of the CO concentration. However, it cannot be assumed that the ratio of CO to H₂ is the same with all stoves – in other cases the H₂ concentration is equal to or greater than that of the CO.

The combustion efficiency is normally taken to mean the ratio of partially burned carbon (CO) to fully burned carbon (CO₂). The CO/CO₂ ratio is used, because with most fuels, the majority of the energy comes from burning carbon. The H₂/H₂O ratio might also be used to measure combustion efficiency.

The CO/CO₂ ratio chart (Figure 5) is often clearer than the CO(EF) or CO₂(EF) measures alone. Measuring the CO and CO₂ at 10 second intervals and plotting their ratio gives a clear indication to us that the combustion efficiency varies with power (Figure 5).

The horizontal grey line shows the common standard (maximum allowable limit for indoor combustion devices) of most national regulations for flame-based domestic cooking appliances. The CO/CO₂ ratio on Low power is significantly higher than the permitted 2%.
As a quality control measure, total carbon, total oxygen and instrument checks (pump flow) are monitored and recorded (Figure 6). Any significant deviations are indicators to discontinue the test or discard a single data set. On the left axis is the sum of all the oxygen and carbon contained in all gases detected by all the cells. In theory it could equal the background O₂ level. However if there is oxygen present in the fuel, the total can rise above ambient especially when combustion is poor. Wet fuel burning badly, for example wet coal, can also produce an O₂ total that is above ambient because of the Water Gas Shift Reaction.

Figure 5  Combustion efficiency: the ratio of CO to CO₂ measured every 10 seconds. (Paraffin Stove 1, small pot)

Figure 6  Data quality check: total oxygen, total carbon, and pump volume (instrument check)

Each set of measurements, typically several hundred, is analysed and plotted separately so that performance during different intervals can be observed (Figure 7). The Green cells are the Task: boiling water. The others are High, Medium and Low power tests with an aggregate at the end. The aggregate includes the five minute transition periods and is performance indicative, not definitive. It is ignored for the plots of performance but available to the reviewer on this chart. If the water cannot be maintained at a boil at any particular power level, the test is done with a cooler pot.

Note that the CO/CO₂ ratio increases from 0.86% to 3.3% while the power level (Watts) drops only 11.5%. Combining these two changes shows that the CO mass emitted per MJ increases by 390% as the heat drops by only 150 Watts. This is significantly different from the wick stove (See Figures 1 & 2) and is not what one expects. Also note that the thermal efficiency drops from 59% to 39% as the power level decreases. This drop, combined
with the actual power decrease of 11.5%, combine to give the user the impression that the fuel consumption rate has dropped because the quantity of heat getting into the pot has diminished. It is often the case that the thermal efficiency on Low is higher than on High power, but it can only be determined if they are calculated separately. Sometimes when turning a stove down from High to Medium, the power output actually rises. Some stoves may not drop in power when switched from Medium to Low.

6. ETHANOL GEL STOVES

The gel fuel stove tests also produced some interesting results. In Figure 8, there is a slight rise in CO as the High power test continues, possibly because the fuel in the reservoir is heating up or because it is emptying the reservoir. There is a dramatic drop in CO when the stove is turned down to Low, indicating excellent combustion. A standard water boiling test conducted on High and Medium might never reveal this remarkably clean burn.

![Figure 8](image)

Figure 8   The CO(EF) for ethanol gel stove 2 indicates a high turn down ratio.

Note: there is no Medium test performed here. The gap between High and Low is denoted ‘Medium’ but the numbers are ignored because the flame and power level are in transition. Once the water had boiled, the power was turned down so the boiling test and the High power test end at the same time.

When looking at the performance of the stove during the whole test (Figure 9) the CO/CO₂ ratio is initially high, and then drops by a factor of more than 5 when switched to Low. The ‘Watts’ column on the far right the power level shows a 60% drop.

This profile of emissions is completely at variance with Paraffin Stove 1 (Figure 7). This is an unexpected result quite unlike the normal profile. Paraffin Stove 1 (PS1) operated for a 10 minute High and 10 minute Low power burn will emit a total of 0.7 g of CO. Ethanol gel stove 2 (EGS2) will emit 1.15g, a factor of 1.64 times as high.

Their average CO/CO₂ ratios are PS1=2.1 and EGS2=3.3. The EGS2 ratio is higher by a factor of 1.6, very close to the results based on a 10 minute High-Low burn. Although the EGS2 has a 57% higher CO/CO₂ ratio on High, the lower Low nearly compensates for it. An EGS2 water boiling test (WBT = boil on High + 45 minutes simmering on Low) shows CO emissions of 1.2 g/litre, only 30% higher than a WBT on the PS1: 0.93 g.

On Medium power the ethanol gel stove 2, instead of emitting 1.10 g/litre of water boiled, might be significantly lower because of a higher thermal efficiency, a higher power, and a lower CO/CO₂ ratio.

Doing a “Medium power boil” calculation for Paraffin Stove 1 determines that it would take 9 minutes longer than on High, at a lower thermal efficiency, with a higher CO/CO₂ ratio. The CO emitted per litre boiled, corrected for temperature, would double from 0.63 to 1.30 merely by operating the stove on Medium instead of High. This is a significant and unexpected result.
THE EFFECT OF THE POT ON THERMAL AND EMISSIONS PERFORMANCE

Emissions of a stove can be affected by the size of the pot, and whether there is a pot present at all, as the pot can dramatically affect the quality of combustion and the air movements through the stove. Figure 10 illustrates the effects on power and thermal efficiency of substituting a large pot with a smaller one.

Note: For each power level three tests are shown with averages and standard deviations.

Figure 10 The relationship between power and thermal efficiency for a small pot (2 litre) and a large pot (6.5 litre)

With a small pot on the stove, the power is 1250 Watts on High, and 300 Watts on Low. The thermal efficiency is 48% on High and 42% on Low. With a large pot on the stove, the power is somewhat reduced to 1120 Watts on High and remains the same as previously with 300 Watts on Low. The thermal efficiency on High increases by one fifth to 58% but drops a little, to about 35% on Low. Similar changes occur with regard to the CO emitted. Figure 11 shows the temperature corrected specific CO emission per litre boiled.

Figure 11 Relationship between power and CO emitted per litre boiled at high power, bringing water to the boil (temperature corrected)

There is a significant increase in the CO emitted per litre boiled if the cook chooses a small pot instead of a large one because the thermal efficiency is lower (Figure 12), so it takes more fuel to bring each litre to a boil.

Figure 12 Specific fuel consumption (grams of fuel per litre boiled) on High Power

In cases where the thermal efficiency increases with pot size the emissions per litre boiled decrease even if the water volume and the power setting are the same for both pots. In
other cases the thermal efficiency on Medium is highest for smaller pots and the specific fuel consumption is minimized, avoiding both extremes.

8. CONCLUSION

Over one hundred sets of data have been collected, burning standardised fuels in eight paraffin and ethanol stoves, each operated at three power levels and cooking two sizes of pot. We found that power and pot size can significantly affect the Specific Fuel Consumption (efficiency) and gas Emission Factors. Select data are presented demonstrating that the heterogeneous testing protocols provide an informative assessment of a stove’s thermal performance and characteristic emissions under realistic operating conditions.

It has been demonstrated that testing at multiple power levels with multiple pot sizes provides an improved assessment of a stove’s thermal performance and its characteristic emissions over ranges of likely realistic uses. Such tests can reveal the optimum operation conditions as well as expose shortcomings of a stove design. Rigid task-based protocols with standard pots and pot-loads can hide a number of defects or erroneously rate as inherently poor, a fuel or stove technology with good potential. Task-based testing neither approximates cooking nor can it provide the important information revealed in the above charts.

Our conclusion is that no single-task stove testing regimen can provide a meaningful performance evaluation of a flame-based cooking appliance. Our results indicate that a heterogeneous test protocol, as developed at the SeTAR Center, incorporating a range of power settings, and various pot and load sizes, is more diagnostic, and hence more useful for stove designers and stove programme managers.

Extrapolations of total CO₂ emissions based on the common water boiling test protocols may also lead to overoptimistic projections of gross emissions reductions from stove replacement programmes – this is a cautionary note for carbon traders, CDM project developers and stove manufacturing and dissemination programmes.

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