A PRELIMINARY COMPARISON OF STOVE TESTING METHODS BETWEEN THE WATER BOILING TEST AND THE *HETEROGENEOUS* TESTING PROTOCOL

Tafadzwa Makonese[1,2], James Robinson[1,2], Crispin Pemberton-Pigott[2] and Harold Annegarn[1,2]

[1] Department of Geography, Environmental Management & Energy Studies,
University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa,
[2] SeTAR Centre, University of Johannesburg
taffywandi@gmail.com

ABSTRACT

Due to the need for the certification of stoves under both Clean Development Mechanism (CDM) and voluntary market projects, there is now a strong drive to create testing protocols and standard operating procedures that simulate the real-world use of stoves. Given the current importance of stove performance tests as a basis for emissions inventories for global climate prediction models, improvements in performance testing are critical to derive representative estimates. This reinforces the need for robust testing protocols that can be used to create performance curves for the inter-comparison of a variety of fuel/stove/task combinations when applied to diverse cooking and space heating needs. Currently stove emission factors are derived from variants of either a Water Boiling Test (WBT) or a Controlled Cooking Test (CCT), in spite of well-documented problems associated with use of these methods. This paper aims to present both a conceptual and preliminary experimental comparison of stove testing methods between the standard WBT and the SeTAR Centre's *Heterogeneous Stove Testing Protocol* (HTP) for thermal and emissions performance, using an ethanol gel stove. Recommendations will be drawn from the results and will have practical relevance for stove project managers and certification bodies to develop a set of criteria for improving existing testing protocols; and for stove developers in guiding improvements in existing stoves and the development of new designs.

Keywords: domestic stoves; cookstoves; water boiling test; controlled cooking test; heterogeneous testing protocol; thermal performance; emissions

1. INTRODUCTION

Improved cookstoves have an extended history in relation to a comprehensive set of issues ranging from local health and environmental implications to global impacts associated with greenhouse gas (GHG) emissions. These issues have been given a new impetus by the launch in late 2010 of the Global Alliance for Clean Cookstoves (http://cleancookstoves.org/). Improvements in performance testing are critical to derive more representative estimates of emissions given the current importance of stove performance tests as a basis for global climate prediction models and IPCC inventories. Emissions from cookstoves contribute significantly to regional estimates of carbon aerosols and inventories of greenhouse gases [1]. Estimations of emissions from cookstoves are important in assessing the global warming benefits of installing improved stoves, and changes in fuel type [2]. They can be useful in the modelling of atmospheric trace greenhouse gas concentrations [3]. These requirements reinforce the need for thorough testing and verification of performance [4]. More importantly, they reinforce the need for robust testing protocols that can be used for the inter-comparison of a variety of fuel/stove combinations from different countries and regions, and the certification of greenhouse gas emissions for air quality management purposes.

When assessing the types of stoves used in the developing world there is, to date, no agreed set of stove testing protocols that have been devised under the guidance of a professional standards setting agency [5]. Consequently, the majority of these protocols are not validated and certified by professional standard certifying bodies. This results in *ad hoc* protocols which are designed for a specific stove testing community or stove programme. This often leads to non-uniformity of the testing regimen, which makes it difficult to compare performance of stoves of varying types and from diverse regions of the globe [6]. Certification of such protocols could be useful in the support of legislation on air quality and for claims under the clean development mechanism (CDM). Hence, the drive should be on the development of robust stove testing protocols with the aim of having them validated and certified by independent certifying bodies.

The majority of fuel/stove thermal performance and emission factor determinations have been derived using controlled testing procedures in simulated kitchens [7,8]. Current Inter-governmental Panel on Climate Change (IPCC) stove emission factors and those often cited in emissions inventories for climate modelling are ultimately derived from the water boiling test [9]. Studies have shown that estimates of emissions using the standard water boiling test are flawed since the method does not simulate real world uses of fuel/stove combinations [2,10,11]. The WBT cannot replicate normal stove use in homes [11], especially in countries such as Mexico or China where the majority of cooking involves tasks that do not involve boiling of water [12]. These estimates may or may not reflect emissions from homes during daily activities. The projection of gas emissions for greenhouse and air quality management purposes cannot readily be made using an invariant standard Water Boiling Test (WBT) because it yields only a single point on a single performance curve. The discrepancy between modelled emissions estimates and measured atmospheric concentrations may be attributed in part to the bias inherent in the constrained water boiling test method [2].

The University of Johannesburg has taken a lead through their *Sustainable energy Technology and Research* (SeTAR) Centre to develop alternative multi-variant testing protocols for a variety of fuel/stove/task combinations. With many of the new products entering the market displaying novel features, there was the need to augment the South African Bureau of Standards (SABS) test for carbon monoxide emissions (a safety performance specification) with a broader evaluation of stove performance, specifically with respect to carbon monoxide emissions of unvented domestic paraffin and ethanol gel fuel stoves. The SeTAR Centre was commissioned to determine the thermal efficiency and gaseous emissions of different fuel/stove combinations. In the process of evaluating these stoves, SeTAR staff was engaged simultaneously in the development of written procedures and spreadsheet calculations that included both primary and secondary combustion effects, leading to the development of what we term the *heterogeneous testing protocol* (HTP).

This paper aims to present both a conceptual and preliminary experimental comparison of stove testing methods between the standard WBT and the SeTAR Centre's *Heterogeneous Stove Testing Protocol* (HTP) for thermal and emissions performance, using tests of an ethanol gel stove as a case study. The model assumptions of the WBT and the HTP are examined in relation to energy efficiency evaluation (economic); the needs of CDM certification (climate protection and energy efficiency); and of indoor air pollution (health and safety). An ethanol gel stove is tested using the respective protocols and emissions factors are calculated and evaluated in appropriate quantities, according to the three different categories of criteria listed above.

2. METHODOLOGY

2.1 CRITERIA FOR COMPARISON

This section seeks to identify a set of criteria that can be used in the development of stove testing protocols that could provide more relevant information for global climate models and inventories, while providing a means to recreate representative emissions profiles in a laboratory setting for technical analyses. The critical issue is not that the task or cooking activity is representative, but that the burn cycle is representative of that which occurs during daily cooking activities in homes [1].

The following criteria will be used to evaluate stove testing protocols for CDM certification:

Does the protocol measure greenhouse gas emissions over an entire cycle that is representative of real-world uses of stoves?

Does the protocol allow for the identification of stove design weaknesses and advantages?

Does the protocol allow for the expression of results in a normalised manner for direct comparisons between different fuel/stove combinations?

2.2 STOVE ASSESSED

An ethanol gel stove was used during the tests and comparisons were made based on its performance. The stove was operated according to the manufacturer's instructions especially in the determination of power settings (*high*, *medium* and *low*). The power of the stove is controlled by means of a lever and the middle power setting was always adjusted to the middle of the range on the control lever. The stove has a small fuel chamber and could only take a maximum of 200 g of the ethanol gel. The fuel used had a lower heating value (LHV) of 19.4 MJ kg^{-1}.

2.3 TESTING METHODS

2.3.1 The Water Boiling Test

The Water Boiling Test (WBT) intends to be a simulation of the cooking process that helps stove designers understand how much fuel is needed to complete a cooking task [13]. The test starts with a high power boiling phase to bring a measured amount of water to a quick boil. Pre-weighed fuel is added as needed at high power setting to bring the water to a quick boil in a standard pot. This part of the test is often referred to as *cold start,* since the tester begins the test with the stove at room temperature [13]. The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test. The second phase, also a rapid boil, is referred to as the *hot start* high power test. In this phase tests are carried out immediately after completion of phase 1, while the stove is still hot. It entails the use of a pre-weighed fuel batch used similarly to boil a measured amount of water in a standard pot. The intent is to identify the differences in performance between a hot stove and a cold stove [13]. A simmering low-power phase follows. The tester determines the amount of fuel required to simmer a measured amount of water for 45 minutes, simulating the cooking of rice and legumes in real-world uses of fuel/stove combinations. Thus, the WBT assesses in three phases, the thermal efficiency, the firepower, and the specific fuel consumption of a stove, where thermal efficiency is defined as a ratio of the work done by heating and evaporating water to the energy consumed by burning wood [11]. One other metric used to characterise stoves is the *turn-down ratio.* The turn-down ratio is reported as a positive real number equal to the fire-power of the stove at *high* power divided by the fire-power of the stove at *low* power.

For the purposes of this study, the ethanol gel stove will be evaluated for thermal performance according to the standard operating procedure outlined in the Water Boiling Test Version 3.0. Data handling and calculations will be done using the Shell Foundation HEH Project WBT data and calculation form [14].

2.3.2 The *Heterogeneous* Stove Testing Method

The essence of the *heterogeneous testing protocol* is to test the stove over the full range of power settings anticipated in domestic use, using more than one pot size. The underlying proposition was that pollutant emissions vary with power setting and can change with the changed flow patterns associated with different pot sizes. Our previous work with paraffin stoves found emissions varied significantly merely by change the pot size [15]. Accordingly, the new protocol requires that the device is operated as per manufacturer's instructions or local fire tending practices, over a range of three power levels (*high*, *medium*, and *low*) to boil water in two representative pot sizes containing respectively 5 and 2 Litres of water.

We adopted an approach of testing in controlled, replicable laboratory conditions, fuel/stove combinations that are typical of real world use, to perform standardised but representative tasks. This approach separates the intrinsic performance of the fuel/stove combination from the vagaries of real world use [16]. Acknowledging that stoves are, by craft or design, adjusted to local conditions, the protocol explicitly allows for the use of a fuel type, size, moisture content and load for which a device was designed or as commonly used. Features of the test protocol require triplicate tests under each condition (stove/fuel combination; power setting; pot size) to obtain estimates and quality assurance on reproducibility. These parameters were selected because they are often ignored in many evaluations of fuel/stove combinations, yet they reflect real world uses of the fuel/stove combinations [5]. Important to the analysis method is an accurate description of the fuel both in terms of major elemental composition as well as the moisture content (wet basis). Standard precautions were taken, such as ensuring a draft free environment (variable heat loss from pot walls can be caused by forced drafts). The data and analysis method are coded into a standard Excel® spreadsheet and include measures to compensate for changes in boiling point with altitude.

For the purposes of this study, the ethanol gel stoves will evaluated for thermal and emissions performance using the standard operating procedures outlined in the SeTAR Centre's *heterogeneous stove testing protocols* [17].

2.3.3 Gaseous Emissions

The *hood* method was used for testing emissions from an ethanol gel fuelled stove. The stove to be tested is placed under an extraction hood (Figure 1). This procedure has the added advantage of enabling simultaneous measurements of emissions and thermal parameters in a systematic and standard manner [18]. Since a high extraction rate may influence the combustion characteristics of the stove [19], an extractor fan was not used for drawing air through the hood and duct. The flue gas sample was taken within the hood, above the stove (Figure 1). The sampling configuration for trace gases included, in sequence, a stainless steel probe, a filter holder, and a flue gas analyser (Testo® 350XL/454). The Testo® measures CO_2, CO, NO_x, NO_2, H_2, H_2S, S, and O_2.

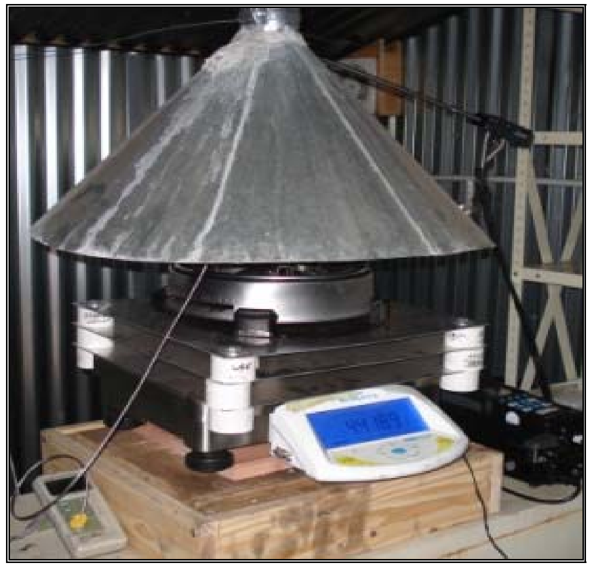

Figure 1: The hood method used for collecting gas emissions

3. RESULTS AND DISCUSSIONS

This section present illustrative experimental and conceptual comparison results from the water boiling test and the heterogeneous testing protocol.

3.1 EXPERIMENTAL RESULTS

Experimental results obtained using the water boiling tests are presented in Table 1.

Table 1: Results from the water boiling test

	WBT (High Power Test)	WBT (Simmering Test)
Time to boil (mins)	27.2 ± 2.6	n/a
Burn rate (g min^{-1})	2.8 ± 0.3	1.9 ± 0.1
Thermal efficiency (%)	75.0 ± 2.0	75.0 ± 1.0
Fire power (watts)	906 ± 92	616 ± 41
Specific fuel consumption# (g L^{-1})	42.6 ± 0.7	
Specific fuel consumption$ (g L^{-1})		70.3 ± 6.4
Turn down ratio*	n/a	1.47 ± 0.20

\# *Boiling task*: To heat water from 25°C to boil
$ *Simmering task*: To maintain water at simmer for 45 minutes
* See text for revised definition

In the WBT data and calculation sheet, the turn-down ratio is not calculated as per definition, but rather as the ratio of the maximum firepower to the power fire setting required to maintain the pot at simmering, a turn down ratio of 1.47 in this case. To keep the water simmering at 3 – 6°C below boiling it was necessary to set the stove at a point between *medium* and *high* power settings. Turning the stove down to a *low* power setting below the *medium* power setting resulted in a rapid drop in water temperature, prompting the testers to turn up the power.

A summary of results from the *heterogeneous protocols* is given in Table 2. The *HTP* tests report a higher turn down ratio of 3.1 compared to the water boiling test when using a small pot (Table 2). Thus results from the WBT reporting 1.47 (using a different definition related to simmering rather than low power setting) may mislead someone looking for a stove with an actual turn down ratio of 3.1.

Table 2: A summary of thermal and fuel consumption results from the *heterogeneous testing protocol* applied to a gel fuelled stove

	Small Pot			Large Pot		
Power Setting	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
Time to boil (mins)	24.6 ± 1.0	n/a	n/a	56.0 ± 1.4	n/a	n/a
Burn rate (g min^{-1})	2.21 ± 0.06	1.01 ± 0.25	0.92 ± 0.16	2.35 ± 0.06	1.15 ± 0.13	0.98 ± 0.08
Thermal efficiency (%)	68.9 ± 4.0	69.6 ± 8.1	73.5 ± 5.4	71.6 ± 2.9	78.1 ± 5.4	80.3 ± 7.2
Fire power (watts)	710 ± 20	330 ± 80	270 ± 40	760 ± 20	370 ± 40	320 ± 30
Specific fuel consumption (g L^{-1})	27.9 ± 1.7			27.3 ± 0.9		
Turn down ratio		3.1			2.7	

Specific fuel consumption is a function of efficiency per se and the fire-power levels at which the stove is operated during the cooking period. The specific fuel consumption was found to be significantly different between the two test methods due to differences in the method of calculation and fire-power levels. The WBT shows a specific consumption of 42.6 g L^{-1} for the boiling task; and 70.3 g L^{-1} for the simmering task (Table 1). This is because the stove was performing two different tasks (bringing water to a quick boil and maintaining a simmer for 45 minutes). The heterogeneous protocols reported a specific consumption for boiling task of 28 g L^{-1} when using a small pot, and 27 g L^{-1} when using a large pot (Table 2). The significant difference between the specific fuel consumption for the boiling tasks emanates from two factors: (i) the absence of a pot lid when conducting the water boiling test as compared to the *heterogeneous protocols* which requires a lid to be used, reducing evaporative losses; and (ii) Different methods of calculation employed. The water boiling test uses the final mass of water boiled and the heterogeneous protocols uses the initial mass of water boiled.

Boiling water demands the highest feasible power output from the stove. There was found to be no significant difference in the time taken to boil water between the two test methods. The *heterogeneous protocols* reported a time of 25 minutes to boil water in a small pot compared to the water boiling test which reported a time of 27 minutes, the only significant difference in the experimental set up being that the WBT specifies that the lid should not be on during the test – leading to loss of energy through evaporation to the atmosphere. The difference in the time to boil is not significant within the recorded standard deviation (±1 STD)

The fire-power at the *high* power setting was found to be significantly different between the two test methods when using the same pot size. The water boiling test reported a fire-power of 906 W (Table 1) compared to the *heterogeneous protocols* which reported a fire-power of 710 W even though the specific fuel consumption was half as much. This difference could be as a result of a marked difference in the operation and performance of the stove during the tests. The water boiling test showed a fire-power of 614W at simmer and the *heterogeneous protocols* reported a fire-power of 380 W at the *low* power setting (Table 2). This significant difference emanates from the fact that power settings used for the two phases were different. The water boiling test used an indeterminate power level for simmering and the *heterogeneous* testing protocol used the lowest sustainable power setting for the *low* power tests due to the use of a pot lid. The test using the *heterogeneous protocols* was able to operate the stove at a lower power.

When employing the *heterogeneous* testing protocol, thermal efficiency does not vary significantly across a range of power settings when user switches between pot sizes (Fig 2).

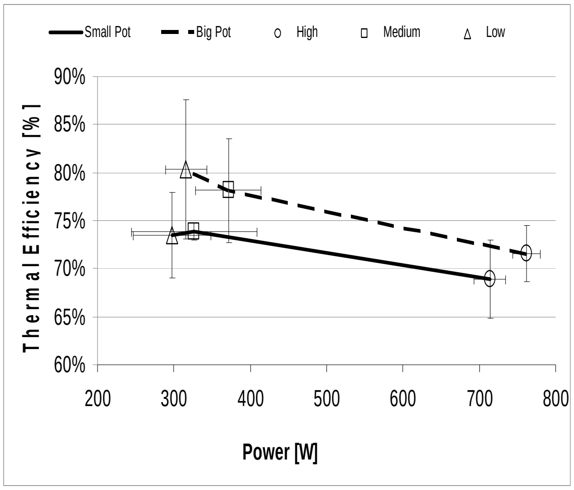

Figure 2: The relationship between firepower and thermal efficiency

There is a significant difference between fire-power on *high* when one switches from a small pot to a large pot (Fig 2). A change from a small pot to a large pot increases the fire-power and the thermal efficiency of the stove. However, the thermal efficiency when switching pot sizes was found not to be statistically significant. Pot size has the potential to affect air dynamics in the space between the stove and the base of the pot.

The efficiency curves such as the one presented in figure 2 allows for assessing the stove across a range of power settings. For example, there was no statistically significant difference between the thermal efficiency and fire-power of the stove at *medium* power and at *low* power respectively. The performance curve presented has implications on design considerations of the stove. Stove developers can try to improve the *medium* power setting to a mid-range of power output levels. These design considerations are easily missed when one employs the classical water boiling test which does not provide performance curves over a full range of power settings.

Like the water boiling test, the *heterogeneous protocols* are also capable of rating a stove's performance when completing a task. The results show that there is no statistically significant difference between thermal efficiency to boil water (task) when employing both methods. The two tests agree because conditions of operation were similar. The *heterogeneous protocols* test the thermal efficiency at different power levels by heating cold water across a 40°C rise, from 30 to 70°C. The time to accomplish this task is noted and the test is repeated several times. An average time to accomplish the task is computed. This allows for a correct evaluation of the thermal efficiency of the stove at different power settings. Running a boil to simmer task is not a test of thermal efficiency. The WBT *claims* to have a thermal efficiency during simmering. However, under perfect conditions there is no work done when simmering because it is a task involving no change in enthalpy *H*. The efficiency at simmering would therefore be reported as zero. The fact that some water boiled out is irrelevant unless one decides to measure the mass of the missing water and report a thermal efficiency number. Boiling off water (evaporating) can be measured but it is by definition not simmering (maintaining a temperature). When one boils water away it is possible to calculate the thermal efficiency by measuring the heat lost as steam as a fraction of the heat invested by the usual method. Because the water is already boiling and the radiant, convective and conductive heat losses are constant and ignored, the efficiency number is not meaningful at *low* power. If the simmer test is run at a higher power, the efficiency would appear to rise and the specific consumption would increase too, raising questions about the intent of the setting and the usefulness of the metrics.

The *heterogeneous* testing protocols entails assessing a stove a cross a range of power settings using a variety of pot sizes (Figure 2). Compared with the water boiling test, the method is a better assessment of fuel/stove combinations because all parameters are measured continuously and the results are presented as a set of performance curves. As a result, it is possible for the stove assessor to see subtle changes in the performance of the stove during a burn cycle and to make reasonable predictions of emissions and performance when conducting cooking tasks or combinations of tasks. All these are important for identifying design weaknesses and advantages of a stove.

3.1 CONCEPTUAL ANALYSIS

This section analyses some of the conceptual differences between the *heterogeneous* protocols and the water boiling test based on a set of criteria presented in 2.1.

Does the method allow for the identification of design weaknesses and advantages?

The method used for the identification of stove design weaknesses and strengths should include continuous measurements of emissions and thermal efficiency so that one can see in detail what is going on in the stove during the combustion process. Since efficiency varies significantly with power output during the different phases of the burn cycle, a single efficiency number may not be a good performance indicator [1,20]. A continuous measurement of the combustion efficiency performance curve of the ethanol gel stove, as indicated in the *heterogeneous* protocols, is given in Figure 2. The profile shows what is happening in the stove across a range of tasks and power settings. Such dynamics in the combustion process of the stove are missed when using the water boiling test which sum the performance metrics from starting and ending values, to give a single integrated number as an output.

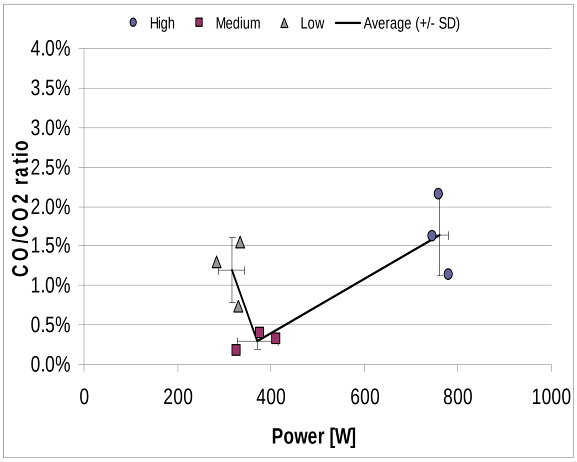

Figure 3: CO/CO_2 versus fire-power profile of an ethanol gel stove showing very good combustion efficiency only at one power level.

Does the protocol measure greenhouse gas emissions over an entire cycle that is representative of real-world uses of stoves?

The *heterogeneous testing protocol* is able to measure greenhouse gas emissions over a range of performance conditions and present the buyer with a performance profile. Using these performance curves the buyer can determine what the performance is likely to be over the operating range of the device. Figure 3 shows a CO/CO_2 versus fire-power performance curve for the ethanol gel stove across a range of power settings. Such profiles are important for assessing the strength and weaknesses of the stoves. From a CDM perspective, these profiles assist assessors in pointing out the most polluting phases of the burn cycle and their potential impact on the environment. It is imperative to assess thermal efficiency and emissions performance of a stove simultaneously. That way trade-offs between thermal and emissions performance can be investigated [21].

Does the protocol allow for the expression of results in a normalised manner for direct comparisons between different fuel/stove combinations?

A hindrance in stove assessments to date is the failure to compare between fuel/stove combinations. The *heterogeneous protocols* allow for the expression of results in a normalised manner for direct comparison between different fuel/stove combinations. Unlike classical water boiling tests, emission factors as used in the *heterogeneous protocols* are normalised to a chosen reference value of zero per cent excess air. The normalisation of these results allows for direct comparisons between different fuel/stove combinations. Results from classic water boiling tests are not normalised to a reference value. The idea is to do a task based test then set a benchmark emission for that task. This makes it impossible to compare between different fuel/stove combinations performing different tasks. The water boiling test does not give information on performance across a range of conditions. The heterogeneous testing protocol on the other hand produces performance (efficiency and emission) curves across a range of conditions.

5. CONCLUSION AND RECOMMENDATIONS

Although the water boiling test and the *heterogeneous protocols* exhibit similar results in thermal efficiency, and time to boil, subtle differences are exhibited in the intent of the methods. The heterogeneous protocol intends to rate the performance across a range of conditions. The water boiling test on the other hand intends to measure the fuel consumed when performing a particular task. As a result differences were found in other parameters (for example fire-power, specific fuel consumption, burn rate and turn down ratio). The differences are as a result of differences in the calculation and analysis methods and the use, or not, of a pot lid. The use of a pot lid has the potential to reduce fuel consumption and represents good cooking practice.

From the illustrative experimental and conceptual results presented in this paper, the *heterogeneous protocols* provide a set of performance curves covering a range of cooking conditions which can then be used to make informed decisions about which stove to promote. The assessment of a stoves performance based on completing a task, even if it is repeated 10 times and known exactly, is not a substitute for a set of performance curves. It can also be shown that there is a wide range of emissions associated within the range of normal variations of pots and power levels of stoves. As a result extrapolation of emissions based on water boiling tests that consider only a maximum power setting (maximum), a simmer setting between the *high* and *medium* power settings (simmering), and boiling water in a single pot (without a lid) may not adequately represent the real world emissions that it is intended to model. Thus the *heterogeneous protocols* provide a more robust measure of evaluation of a diverse range of stove and fuel combinations for Clean Development Mechanism intercomparison and certification purposes.

In as much as it been demonstrated that the *heterogeneous protocols* provide a better assessment of a variety of fuel/stove combinations, it should be noted that these tests were wholly lab-based. Laboratory results cannot be a firm basis for planning stove-diffusion programmes, since the actual field performance can be substantially lower than those obtained under controlled conditions. There is, therefore, a need for the *heterogeneous* stove testing protocols to be evaluated against in-field assessments of fuel/stove combinations to assess how close they simulate real world uses of stoves.

6. ACKNOWLEDGEMENTS

We wish to thank all staff at the SeTAR Centre and Maxwell Vhareta (School of Physics, University of the Witwatersrand). This study was funded in part by an NRF Focus Area bursary to TM, and by a University of

Johannesburg Quick Wins Grant for the EnerKey Sustainable Megacities programme.

7. REFERENCES

[1] Johnson, M., Edwards, R., Berrueta, V. and Masera, O.: "New Approaches to Performance Testing of Improved Cook-stoves", *Environ. Sci. Technol.* Vol. 44, 2010, pp. 368-374.

[2] Johnson, M., Edwards, R., Frenk, C.A. and Masera, O.: "In-field greenhouse gas emissions from cook-stoves in rural Mexican households", *Atmospheric Environment*, Vol. 42, 2008, pp. 1206-1222.

[3] Tan, Q., Chameides, W.L., Streets, D., Wang, T., Xu, J., Bergin, M. and Woo, J.: "An evaluation of TRACE-P emission inventories from China using a regional model and chemical measurements" *Journal of Geophysical Research - Atmospheres*, Vol. 109, 2004, D22305, doi:10.1029/2004JD005071.

[4] MacCarty, N., Ogle, D., Still, D., Bond, T. and Roden, C.: "A laboratory comparison of the global warming impact of five major types of biomass cooking stoves", *Energy for Sustainable Development*, Vol. XII, No. 2, 2010, pp. 5–14.

[5] Makonese, T., Robinson, J., Pemberton-Pigott, C., Molapo, V. & Annegarn, H. "A *heterogeneous* testing protocol for certifying stove thermal and emissions performance for GHG and air quality management accounting purposes". Paper presented at *A&WMA Conference*, 10-14 May 2010, Xian, China, In press: *JAWMA*, 2011.

[6] Taylor, P.R.: *The Uses of Laboratory Testing of Biomass Cook-stoves and the Shortcomings of the Dominant U.S. Protocol*, MSc Thesis, Iowa State University, Ames, Iowa, 2009.

[7] Smith, K.R., Uma, R., Kishore, V.V.N., Lata, K., Madne, S., Rao, G., Zhang, J., Rasmussen, R.A., Khalil, M.A.K. and Thorneloe, S.A.: *Greenhouse Gases from Small-Scale Combustion Devices in Developing Countries Phase iia: Household Stoves in India*, U.S. EPA-600/R-00-052, U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC, 2000.

[8] Zhang, J., Smith, K.R., Ma, Y., Se, S., Jiang, F., Qi, W., Liu, P., Khalil, M.A.K., Rasmussen, R.A. and Thorneleo, S.A.: "Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors", *Atmospheric Environment*, Vol. 34, 2000, pp. 4537-4549.

[9] Johnson, M., Edwards, R., Ghilardi, A., Berrueta, V. and Masera, O.: "Why current assessment methods may lead to significant underestimation of GHG reductions of improved stoves", *Boiling Point*, Vol. 54, 2007, pp. 11-14.

[10] Roden, C.A., Bond, T.C., Conway, S., Pinel, A.B.O., MacCarty, N. and Still, D.: "Laboratory and field investigations of particulate and carbon dioxide emissions from traditional and improved cook-stoves", *Atmospheric Environment*, Vol. 43, 2009, pp. 1170-1181.

[11] Berrueta, V.M., Edwards, R.D. and Masera, O.R.: "Energy performance of wood-burning cookstoves in Michoacán, Mexico", *Renewable Energy*, Vol.33, 2008, pp. 859-870.

[12] Dutt, G. and Ravindranath, N.H.: "Alternative bioenergy strategies for cooking" in *Renewable Energy: Sources for Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams (Eds), Island Press, Washington DC, 1993.

[13] Bailis, R., Ogle, D., MacCarty, N., Still, D., Edwards, R. and Smith, K.R.: *The Water boiling Test Version 3.0: Cook-stove Emissions and Efficiency in a Controlled Laboratory*, Technical Report, University of California, Berkley.

[14] Shell Foundation: *Water boiling test (WBT) data calculation sheet 3.0*, Shell Foundation HEH Project, Berkley Air Monitoring Group, Berkley, 2007. http://www.berkeleyair.com/publications/cat_view/42-publications (accessed 17/02/2011).

[15] Makonese, T., Robinson, J. and Annegarn, H.J.: "South African paraffin stoves: A comparative analysis of emissions and thermal performance", *Proceedings of the National Association for Clean Air (NACA)*, Protea Hotel, Polokwane, 2010.

[16] Robinson, J., Makonese, T., Pemberton-Pigott, C. and Annegarn, H.J.: "*Heterogeneous* stove testing protocols for emissions and thermal performance" in *Proceedings of the 18th Domestic Use of Energy Conference*, Cape Peninsula University of Technology, Cape Town, 2010, pp. 41-47.

[17] SeTAR SOP # 1.05: *The heterogeneous procedure for thermal performance and trace gas emissions*, SeTAR Internal Report No. 01-10, University of Johannesburg, 2010.

[18] Zhang, J. and Smith, K.R.: "Emissions of carbonyl compounds from various cook-stoves in China", *Environmental Science and Technology*, Vol. 33, No. 14, 1999, 2311-2320.

[19] Bhattacharya, S.C., Albina, D.O. and Salam, P.A.: "Emission factors of wood and charcoal-fired cookstoves", *Biomass and Bioenergy*, Vol. 23, 2002, pp. 453-469.

[20] Prasad, K.K., Sangen, E. and Visser, P.: "Woodburning Cookstoves" In *Advances in Heat Transfer*, J.P. Hartnett, F. Thomas, J. Irvine (Eds), Elsevier, Vol. 17, 1985, pp. 159-317.

[21] Ahuja, D.R., Veena, J., Smith, K.R. and Venkataraman, C.: "Thermal Performance and Emission Characteristics of Unvented Biomass-burning Cook-stoves: A Proposed Standard Method for Evaluation", *Biomass*, Vol. 12, pp. 247-270.

AUTHOR(S)

Principal Author: Tafadzwa Makonese is an MPhil (Energy Studies) candidate at the University of Johannesburg. His main focus is on the development of alternative stove testing protocols for different fuel/stove combinations and

the determination of trace gas and particulate emissions from these devices. taffywandi@gmail.com

Co-author:

Prof Harold Annegarn has researched atmospheric 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 Megacities, through the EnerKey programme in partnership with the University of Stuttgart; and the development and testing of improved 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 Asia as well as with renewable and fossil fuel electricity generation in the UK. He has experience in the research, operation, engineering and development of various energy technologies, including stoves. Jamesrobinson77@gmail.com

Co-author:

Crispin Pemberton-Pigott has worked with dozens of Appropriate Technologies for 30+ years, designing stoves and labour-enhancing equipment. He won the DISA Chairman's Award 2004 for the Vesto Stove made by his company, New Dawn Engineering. A co-founder of the Eastern Cape Appropriate Technology Unit, the Renewable Energy Association of Swaziland and the Industrial Designers Association of South Africa, he presently he advises two Mongolian clean air projects and the SEET Laboratory. He is the senior technical advisor at the *Sustainable Energy Technology And Research* (SeTAR) Centre at the University of Johannesburg. He volunteers at ETHOS and SABS co-writing stove standards and test protocols and has advised engineering student projects at the Universities of Alberta (Edmonton) and Waterloo in Canada and Dartmouth College, USA. For more information visit: www.newdawnengineering.com crispin@newdawn.sz

Presenter: The paper is presented by **Tafadzwa Makonese**.