Energy for Sustainable Development 16 (2012) 3–12

Contents lists available at SciVerse ScienceDirect

Energy for Sustainable Development

Influence of testing parameters on biomass stove performance and development of an improved testing protocol

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ARTICLE INFO

Article history:
Received 28 May 2010
Revised 25 October 2011
Accepted 26 October 2011
Available online 27 November 2011

Keywords:
Biomass
Combustion
Cookstoves
Test protocol

ABSTRACT

Biomass fuels are used by nearly half the world's population on a daily basis for cooking. While these stoves often look simple in appearance they are notoriously difficult to test. By their very nature biomass stoves are typically fairly uncontrolled devices which often exhibit a large amount of variability in their performance. In order to characterize a stove and understand the processes which are occurring inside, and through this begin to design better stoves, this variability and uncertainty needs to be reduced as much as possible. A parametric study was conducted to better understand what factors lead to variability and uncertainty in cookstove test results and should be controlled in order to obtain repeatable results. Using the Water Boiling Test as a starting point, it was found that significant reductions in test variability could be achieved through minimizing the amount of water vaporization which occurs during the test. Uncertainty was further reduced by using fuels with consistent moisture contents. Based on these findings a new testing methodology, the Emissions and Performance Test Protocol, has been proposed and the benefits of moving to this method presented.

Introduction

Tables 2, 3, 5, 6, Fig. 9

Half of the world's population cooks domestically with simple biomass stoves (Bruce et al., 2000). This widespread practice generates massive amounts of indoor air pollution (IAP) which has been linked to 2.6% of global illness (Rumchev et al., 2007). From an environmental perspective, unsustainable biomass use has resulted in deforestation and significant levels of greenhouse gas production (including black carbon emissions) (Smith et al., 2010). Although improved cookstoves have been developed which significantly reduce emissions of toxic gases and increase thermal efficiency, the inherent stochastic nature of biomass combustion, combined with natural variations in use, make quantifying stove performance challenging. There are limited protocols (Bailis et al., 2007b; Bureau of Indian Standards, 1991; Xiangjun, 1993) and no formal standards have been developed specifically for domestic biomass cookstoves. While there are many factors necessary to successfully design and disseminate a clean burning cookstove, one is a testing protocol which results in consistent, reliable, and repeatable results. While testing protocols alone will not result in large scale adoption of improved cookstoves, they will ensure that clean, fuel efficient, highly reliable products with a high chance of success will be available for dissemination. The methods of evaluating stove performance currently being used fail to yield consistent results or rely on unreasonable correction factors. This has resulted in a lack of high quality, comparative data that is needed to support stove design efforts. The aim of this study is to determine the effects of controllable test parameters on the results of biomass cookstove testing to help inform the development of a highly repeatable test protocol.

One of the most common protocols currently in use to evaluate stove performance is the Water Boiling Test (WBT) used to measure the thermal efficiency of a cookstove. However, the WBT is increasingly used to measure not only the efficiency, but also the emissions of cookstovess. The WBT is explored parametrically using both experimental and analytical methods to understand sources of variation and uncertainty which arise in the protocol. The Emissions and Performance Test Protocol, a modification which addresses these sources of uncertainty, is proposed and evaluated as an improved method.

Background

The gaseous and particulate emissions released from biomass combustion are known to be damaging to both the environment and human health. Biomass combustion in traditional stoves drastically reduces indoor air quality and contributes to 2 million deaths annually from acute lower respiratory disease (Bruce et al., 2000). The World Health Organization (WHO) has linked smoke inhalation from biomass combustion with a doubling in the occurrence of respiratory disease in children (Khalequzzaman et al., 2007; WHO/UNDP, 2004). The implications of biomass cookstove use are not limited to local impacts and human health factors. Wood cookstove use can

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0973-0826/$ – see front matter
doi:10.1016/j.esd.2011.10.008

Table 1
Experimental matrix and number of test replicates conducted.

Test parameter	Test version	Replicates
Fuel geometry	Small	3
	Medium	3
	Large	3
Fuel moisture content	4%	2
	7%	3
	13%	2
	30%	2
Pot geometry	1	3
	2	3
	3	3
	4	3
	5	3
	6	3
Pot insulation	No insulation	3
	Insulation	3
Total		42

Table 3
Statistical significance of moisture content on stove performance using an unpaired Student *t*-test analysis, differences considered statistically significant at p ≤ 0.05.

	4%	7%	13%
Wood use			
7%	0.16		
13%	0.90	0.14	
30%	0.47	0.10	0.46
CO			
7%	0.78		
13%	0.01	0.15	
30%	0.43	0.94	0.04
PM			
7%	0.16		
13%	0.25	0.54	
30%	0.25	0.93	0.60

increase deforestation and may account for 1–2% of annual global warming (Ahuja, 1990) if not done sustainably. In addition, the particulate matter released during biomass combustion can be carried hundreds of miles from its source (Naeher et al., 2007) having global environmental impacts (U.S. Environmental Protection Agency, 2008).

Test standards will be required in order to achieve the significant improvements in biomass cookstove emissions needed to have an impact on human health and the global environment. To reach the billions of people in need of clean stoves, the validity of the standards will need to be recognized by governments on an international level and will need to meet the requirements of industry. While there is a time and place for small scale stove dissemination, it will likely take mass production and the active involvement of business and industry specialists, to produce the millions of stoves which are required. For government, business, and industry to participate in stove dissemination, a reasonable, realistic, and repeatable testing protocol will be required.

Volunteers in Technical Assistance

Some of the first serious efforts to develop test protocols specifically for biomass cookstoves was facilitated by Volunteers in Technical Assistance (VITA) in 1982. The VITA tests were an attempt to improve the comparability of stove designs, help groups testing stoves to get the most from their results, to aid in reliable interpretation of results. A key outcome of the VITA sponsored event was the formalization of three protocols for assessing fuel efficiency for cookstoves; the Water Boiling Test (WBT), the Kitchen Performance Test (KPT) and the Controlled Cooking Test (CCT). The WBT was designed to be a simple laboratory test to be used to compare fuel consumption between stove designs and acknowledged that it may not directly correlate to stove efficiency during actual cooking. The KPT was designed as a field evaluation of stove fuel efficiency in homes during actual cooking practices. While both the WBT and KPT can provide useful information they in some ways represent the extremes of cookstove protocols. The WBT and lab test with only limited similarities to actual use and the KPT a fairly uncontrolled test but extremely representative of what the end user will see. The CCT was developed to be an intermediary test, a test where stoves are used to cook real meals but under more repeatable conditions (Bussman et al., 1985).

Revised testing protocols — Household Energy and Health Programme

Revised versions of the WBT, KTP, and CCT protocols were prepared for the Household Energy and Health Programme in 2004 and 2007 with support from the Shell Foundation. The latest WBT version can be found online (The Partnership for Clean Indoor Air, 2010; University of California, Berkeley, 2011). While the tests are similar to those developed in collaboration with VITA in the early to mid 1980s minor modifications have been made to reduce variability and increase the usability of the protocols.

It can be argued that revised WBT and the work of the Household Energy and Health Programme are some of the most important stove development work which has occurred in the past 30 years. A special issue of Energy for Sustainable Development released in 2007 provides an excellent overview of recent stoves research and projects which have resulted from the Household Energy and Health Project, many of them utilizing the revised WBT protocol (Smith, 2007).

Carbon credits and the Gold Standard

The concept of using carbon credits or carbon financing as part of an improved stove program is gaining ever increasing attention. One methodology being utilized to assess impact is based on the Kitchen

Table 2
Statistical significance of wood geometry on stove performance using an unpaired Student *t*-test analysis, differences considered statistically significant at p ≤ 0.05.

	Small	Medium
Wood use		
Medium	0.51	
Large	0.92	0.56
CO		
Medium	0.87	
Large	0.69	0.54
PM		
Medium	0.08	
Large	0.22	0.87

Table 4
Material and dimensions of cook pots tested.

Pot	Material	Width (cm)	Height (cm)	Mass (kg)
1	Stainless steel	25.5	25.5	0.75
2	Stainless steel	25.5	16.5	0.83
3	Stainless steel	23	20	0.65
4	Aluminum	25.5	18	0.32
5	Porecelain coated mild steel	24	18.5	0.58
6	Porecelain coated mild steel	35.5	25.5	1.19

Table 5
Statistical significance of a reference to pot size on stove performance using an unpaired Student *t*-test analysis, differences considered statistically significant at $p \leq 0.05$.

Temperature rise					
	Pot 1	Pot 2	Pot 3	Pot 4	Pot 5
Pot 2	0.02				
Pot 3	0.07	0.91			
Pot 4	0.09	0.77	0.75		
Pot 5	0.01	0.34	0.62	0.36	
Pot 6	0.22	0.51	0.54	0.72	0.26

Performance Test (KPT). It is the only method accepted for the Gold Standard Voluntary methodology (The Gold Standard, 2011; Climate Care, 2010) and has recently been added as an acceptable option under the Clean Development Mechanism (CDM) methodology. While the KPT has many desirable aspects in gauging customer acceptance of a technology the authors have a number of concerns with the particular implementation of the protocol being suggested for carbon programs. By its very nature the KPT is an uncontrolled test, it is nearly impossible to separate the user from the stove when using the KPT protocol. Because the test is uncontrolled an unusually good or bad day of testing can have a massive impact on the perceived impact of a stove. This also means that any one test result is not replicable because of the number of variables that are uncontrolled. This leaves a lack of transparency and ability for independent validation of results both of which carbon markets must have to maintain legitimacy The most concerning aspects of the Gold Standard implementation of the KPT is the lack of standardization for implementing the tests which is being allowed. The test can use either paired, independent, or single sampling methods. Not all communities will have traditional stoves with the same baseline performance creating a potential for huge uncertainty when attempting to quantify improvement. It is also felt that 3 days of sampling will not be sufficient to capture the natural day to day variations which arise during normal cooking habits. While the authors agree that carbon credits could play a beneficial role in stove programs it is felt that the current methodologies being proposed could do more harm to the system than good. In order to gain credibility for clean cookstoves in the carbon market a robust, reliable, and repeatable protocol will need to be used.

Bureau of Indian Standards

In 1983 the Department of Non-Conventional Energy Sources (DNES) in India began a program to promote the introduction of improved biomass stoves. The DNES launched the National Programme on Improved Chulhas (NPIC) seeking to reduce fuel use, limit deforestation, and improve air quality in the home through more efficient cookstoves (Regional Wood Energy Development Programme in Asia, 1993). In conjunction with the program, the Bureau of Indian Standards (BIS) developed a testing process to evaluate and certify biomass stoves. The BIS protocol uses a set amount of fuel, based on a stove's designed heat production rate, and determines heat transfer efficiency to a cooking pot. The test calls for determining heat transfer and emissions from specified amount of wood and does not attempt to replicate real use conditions (Bureau of Indian Standards, 1991).

Table 6
Statistical significance of changing test protocol on stove performance using an unpaired Student *t*-test analysis, differences considered statistically significant at $p \leq 0.05$.

Cold start wood use	0.70
Cold start carbon monoxide	0.10
Hot start wood use	0.85
Hot start carbon monoxide	0.10
Simmer start wood use	0.00
Simmer start carbon monoxide	0.49

The state standard of the People's Republic of China

The largest improved stove program to date was conducted by the Chinese government through the National Improved Stove Program. The Testing Method for the Heat Properties of Civil Firewood Stoves is similar to the BIS method in that it only accounts for heat transfer efficiency, not applicability to cooking practices (Xiangjun, 1993).

Combustion and heat transfer in biomass stoves

Combustion process

Although a full discussion of biomass combustion is beyond the scope of this paper a basic overview has been provided to ensure clarity of terminology and as a background for theoretical discussion points. The importance of the parameters tested can be better understood with an understanding of how they relate to the combustion process.

Biomass combustion is a complex process with chemical reactions occurring in the liquid, solid, and gas phases simultaneously. Over 200 compounds have been identified to exist in the gas phase alone during biomass combustion. Fuel composition, wood knots, and growth rings are only a few of the many factors that impact the combustion process (Penner et al., 1992). Wood combustion is typically broken into 4 stages: drying, pyrolysis, combustion, and surface oxidation (Kituyi et al., 2001). The transitions from one stage to the next are indefinite but approximate temperatures and processes occurring in each stage are shown in Fig. 1 (White and Dietenberger, 2001).

Drying

Moisture limits the local temperature in the wood until the water has been vaporized. The energy required for vaporization of water in the fuel will lower the temperature in the combustion chamber, slowing the rate of combustion. Moisture in the fuel will also have the effect of reducing the adiabatic flame temperature and increasing the amount of air required for complete combustion. High moisture content fuels will have a decreased production rate of volatiles during pyrolysis and increased char formation (Baldwin, 1987; Tillman et al., 1981). Unless otherwise noted all moisture contents in this document will be on a dry basis.

Pyrolysis

Pyrolysis is the chemical degradation of a material due to heating. The vibrations of a material's bonds increase in frequency as temperatures increase until those bonds eventually fail, emitting gases (Emmons and Atreya, 1982). Hydrocarbons, such as methane and acetaldehyde, CO2, CO, hydrogen gas, and water vapor are all released during the pyrolysis process. If the temperature of the volatile gases decreases they will condense into creosote and tars (Tillman et al., 1981). These tars are corrosive and can eventually lead to clogging or foiling of a stove (Karsky, 1980). The chemical composition of the compounds released during pyrolysis depends on the heating rate, ambient conditions, fuel moisture content, and the structure of the fuel (Tillman et al., 1981).

The chemical structure and composition of a fuel has an impact on the pyrolysis process. Wood is primarily composed of cellulose, hemicellulose, and lignin. Cellulose forms the majority of the fiber bundles which run the length of the fuel and comprises roughly 50% of the wood on a mass basis. Variations in cellulose arrangement and composition are the primary factors in determining the properties a wood species will exhibit. Hemicellulose has a similar chemical composition to cellulose but is comprised of amorphous random bonds instead of a well ordered structure. The tangled, random bonds in hemicellulose

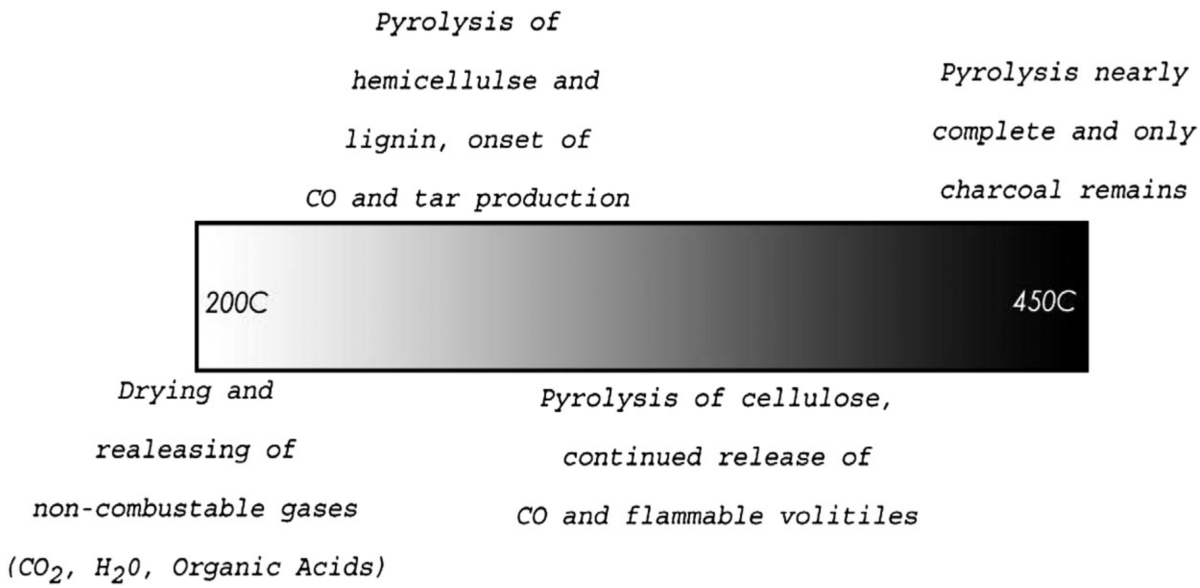

Fig. 1. Stages of wood combustion and associated chemical compounds with respect to increasing temperature.

help to bind cellulose bundles together. Lignin helps hold individual wood cells together (Forest Products Laboratory (US), 1974). The remainder of the wood is primarily inorganic materials, often referred to as ash. The composition and quantity of ash will change with location in a sample of the fuel and between wood species (Tillman et al., 1981).

Combustion

As pyrolysis gases are emitted they will diffuse and mix with the surrounding air. If sufficient mixing with oxygen occurs before leaving the reaction zone, and sufficient energy is available, pyrolysis gases will combust (Emmons and Atreya, 1982). If either the energy or the oxygen needed is not available, gases will escape the flame region forming PIC or condensing into smoke (Haynes and Wagner, 1981). The rate at which these volatile gases mix with oxygen is often a limiting factor in the combustion process (Baldwin, 1987). Volatile gases typically account for $\frac{2}{3}$ of the net energy released during combustion, the remaining $\frac{1}{3}$ attributed to charcoal oxidation (Penner et al., 1992).

Surface oxidation

The charcoal which remains after the majority of volatile gases have been driven off contains significant amounts of energy. The charcoal surface reacts with oxygenated molecules in the air and form into either carbon monoxide or carbon dioxide, releasing energy to the surroundings (Grabke, 1999). Charcoal surface oxidation rates are primarily a function of the rate oxygenated molecules can diffuse to the fuel surface (Grabke, 1999; Matsui and Tsuji, 1987). As solid carbon is pulled from the charcoal an ash layer, composed primarily of silicon dioxide and calcium oxide (Tillman et al., 1981), is left on the surface. The ash layer acts like insulation reducing heat transfer from the charcoal and slowing the overall reaction. As the surface temperature of the charcoal rises above 1300 K reactions forming CO exceed those forming CO2 (Matsui and Tsuji, 1987) and high concentrations of toxic gases are released.

Influence of radiation

Although radiation can be a small fraction of the energy transferred to a cook pot, it is crucial to sustaining the combustion process. As radiation is emitted, a portion of the energy is reabsorbed by the

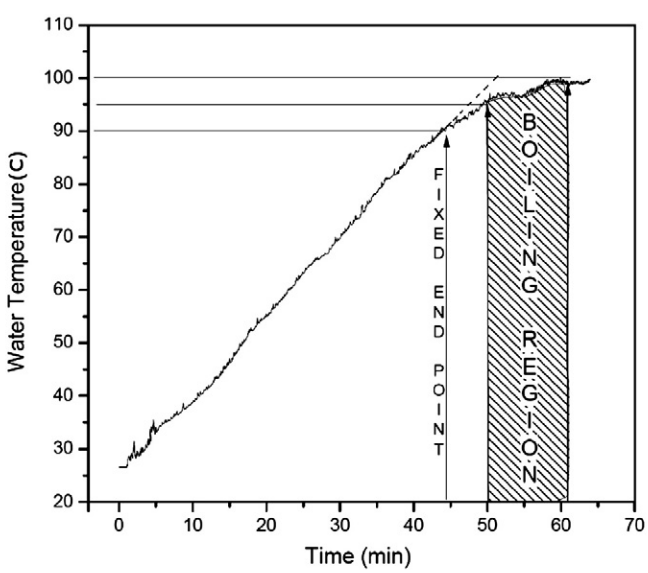

Fig. 2. Ambiguity of boiling point due to slight variations in vaporization temperature.

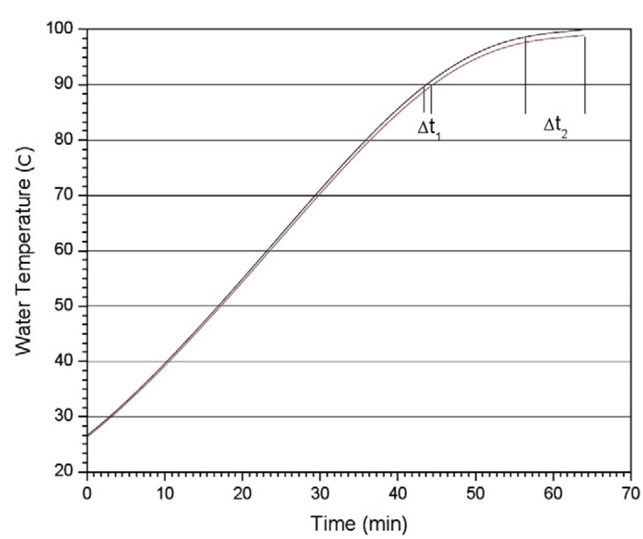

Fig. 3. Uncertainty in test duration due to slight variations in water boiling point.

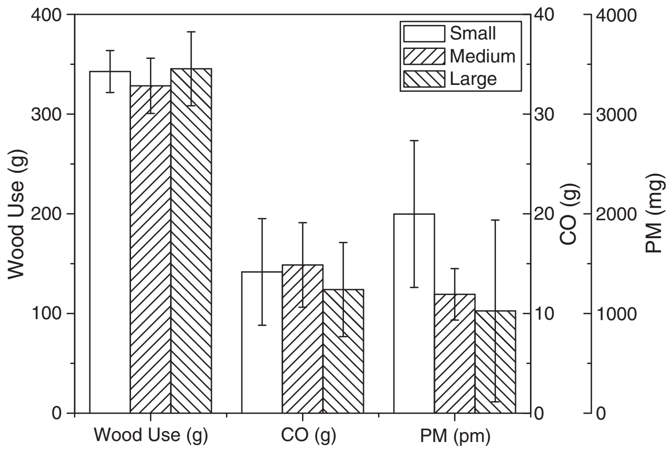

Fig. 4. Effect of fuel size on wood use, carbon monoxide, and particulate matter. Uncertainty bars represent one standard deviation.

fuel providing the energy necessary for continued decomposition and combustion (Baldwin, 1987). The size, composition, and temperature of soot particles play an important role in flame temperature, chemistry, and heat transfer (Kennedy et al., 1996).

Heat transfer

Traditional stoves typically have thermal transfer efficiencies of less than 15% (Barnes et al., 1994; Gupta et al., 1998). This low efficiency is based on the assumption that a large fraction of the energy being produced is "wasted," which is not always accurate. Energy from the combustion process can be split into four groups: energy to the pot, energy to sustain pyrolysis and combustion, energy to heat the stove, and energy in the exhaust gases. When discussing thermal efficiencies it has to be decided what is useful energy and what is wasted. The first two are always considered "useful" but the designed function of the stove will determine the desirability for the others. Depending on the situation, the heating of the stove body and the releasing of hot gases into the room may be desirable, for instance, in locations where the stove is also used as a room heater. In warmer climates the energy released to the room is undesirable and considered "wasted" energy. Due to the ambiguity in thermal efficiency calculations it will not be discussed in much detail here.

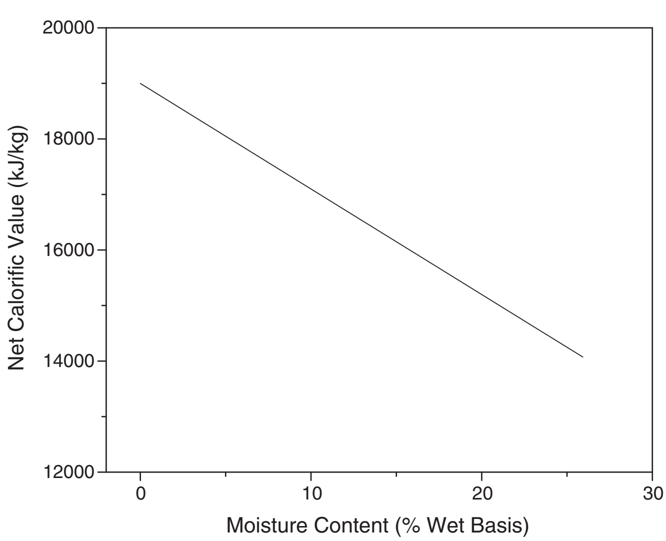

Fig. 5. Effect of moisture content on net wood calorific value (Van Loo and Koppejan, 2008).

Energy is created and dispersed differently depending on the stove used and how it is operated. The energy needed to sustain combustion is a function of combustion rate and ambient conditions but typically will be quite small when compared to overall heat transfer (Baldwin, 1987). Heat transfer to or from a cooking pot or stove body depends on their relation to the combustion process, temperature, material, surface area and mass. The energy absorbed by the body of the stove increases as the specific heat, the surface area, and the mass increase. As the stove and pot temperatures change the amount of energy being transferred also changes.

Analysis of testing procedure

The goal of a testing standard is to define a procedure which is highly repeatable and reasonably representative of real world conditions. Understanding the influence of different factors on results is crucial to developing a good standard. Many of the protocols which have been developed for testing cookstoves fall into one of two categories: tests based on energy transfer, and tests based on completion of a specific task. Task oriented protocols, such as the KPT and CCT, have the advantage of capturing the nature of the stove and predicting the stove performance a user will experience. The KPT is one of the most accurate ways of assessing field fuel economy of a stove design. The downside to task based tests is significantly increased levels of variability. An energy transfer test such as the WBT or the revised protocol presented here, alternatively, allows for more control and repeatability but may fail to capture the nature of how the stove will perform during real use.

Successes, limitations, and goals of test protocols

The Chinese and Indian cookstove standards investigated attempt to determine the amount of energy which can be transferred to the pot. Both standards have achieved an accurate method of determining heat transfer efficiency and provide adequate time to average out the transient nature of a stove. Unfortunately neither standard considers how the stove is going to be used by a cook. While the Water Boiling Test has the advantage of being similar to cooking practices making comparisons with it can be difficult due to large variation between test replicates. A fundamental limitation of the Water Boiling Test is just that, the test only boils water. While boiling and simmering are common cooking practices it is far from ubiquitous and as such the WBT has the potential of underrating stoves designed for different foods and other cultural practices (Bailis et al., 2007a; MacCarty, 2010).

Energy Transfer

In the authors' opinion, measuring energy transfer is the most promising approach to developing a testing protocol but measuring energy transfer becomes difficult as vaporization temperatures are approached. The temperature at which boiling occurs is dependent on altitude, ambient barometric pressure, and water purity and will change with location and conditions. For example, at an altitude of 1500 m water boils at 94.5–95.5 °C, depending on the barometric pressure, while water will boil closer to 100 °C at sea level. As can be seen from Fig. 2 the ambiguity of boiling points can cause considerable test uncertainty. While correction factors have been used in the past to account for testing in different locations (Bailis et al., 2007b), changing the test temperature range allows the same test procedure to be used, in most locations, without introducing additional corrections or uncertainties. With the use of a single fixed temperature, below the boiling point, all stoves are required to transfer the same amount of energy regardless of location or current conditions.

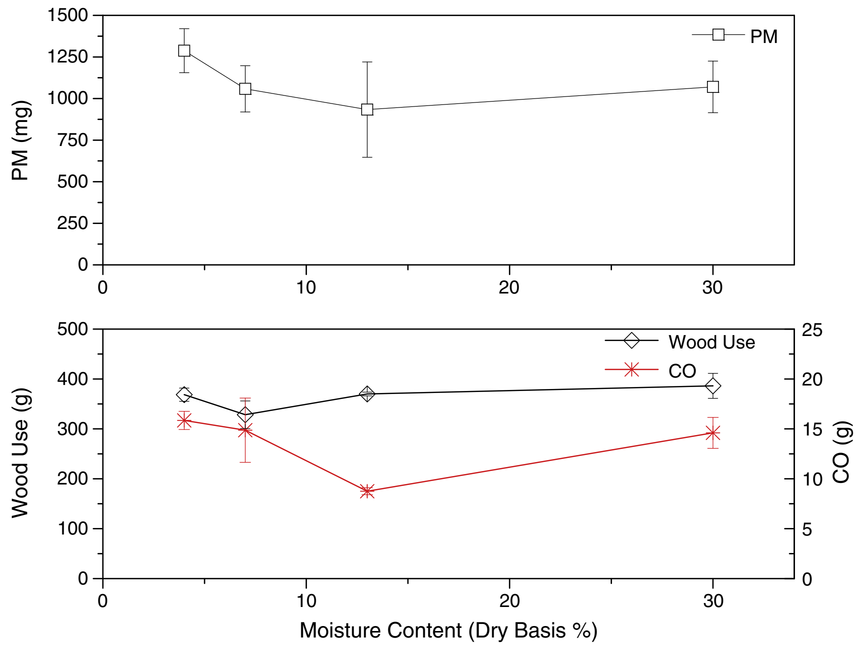

Fig. 6. Effect of changing moisture content on stove performance. Uncertainty bars represent one standard deviation.

As the temperature of the water approaches its boiling point vaporization will occur. The net energy added to the water is a function of heat transfer to the water from the stove and from the water in the form of steam. Returning to Fig. 2, the dashed line represents the progression of water temperature if no vaporization occurred under constant heat addition conditions. Real water temperature profiles will deviate from the ideal as energy is removed through vaporization. Correcting for vaporization is difficult as the amount of energy lost is dependent on temperature. As the water temperature rises the amount of energy leaving the pot due to vaporization increases. Shown in Fig. 3 is the effect of slight differences in boiling temperature on test duration. Using Fig. 3 as an example, it can be seen that an uncertainty of 1 °C in the boiling temperature can increase uncertainty in test duration by 5 times, Δt_2 1.

In an ideal case, no energy leaves the water in the form of steam, and heat transfer to the pot can be calculated using Eq. (1). With vaporization the real heat flux leaving the pot as steam can be found from Eq. (2). In most testing situations the mass rate of water vaporization is not known to any degree of accuracy making the equation difficult to solve accurately. Although assumptions could be made about the temperature at which vaporization is occurring, this uncertainty is unnecessary when a slight variation in test temperature removes the problem altogether.

$$qw = m * Cp * (dT/dt) \qquad (1)$$

$$qv = hfg * (dmv/dt) \qquad (2)$$

Where:

qw	heat flux into water (W)
qv	heat flux leaving the water in the form of steam (W)
m	mass of water in pot (kg)
Cp	Specific heat of water (kJ/kg-K)
dT/dt	temperature rate (K/s)
hfg	heat of vaporization (kJ/kg)
dmv/dt	mass rate of water vaporizing (kg/s)

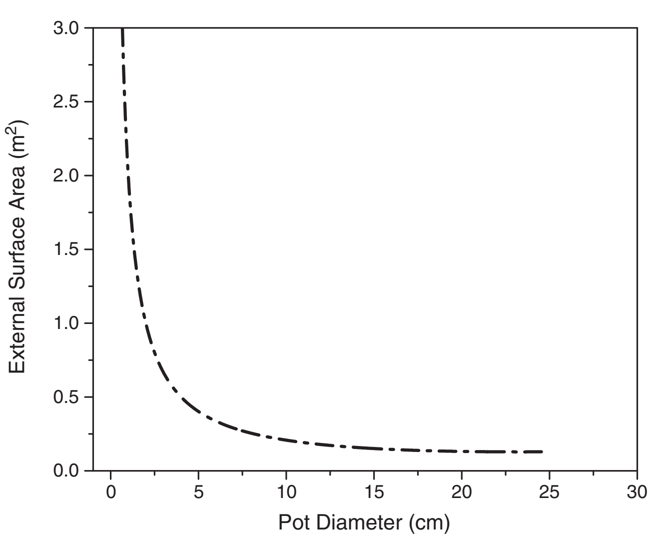

Fig. 7. External surface area vs pot diameter for a constant volume.

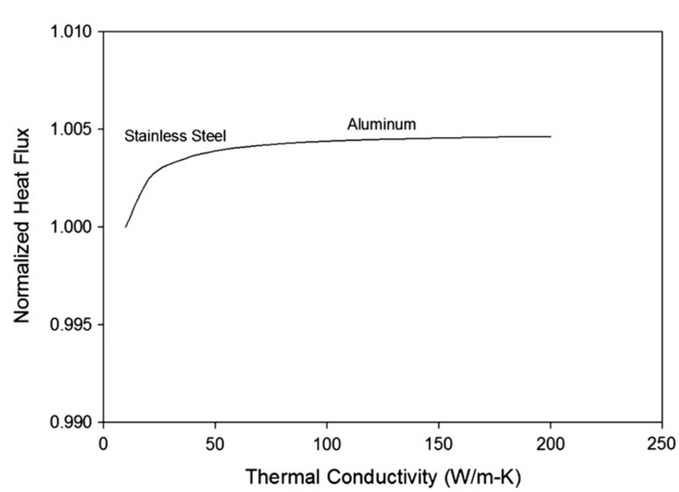

Fig. 8. Influence of pot conductivity on heat flux into water.

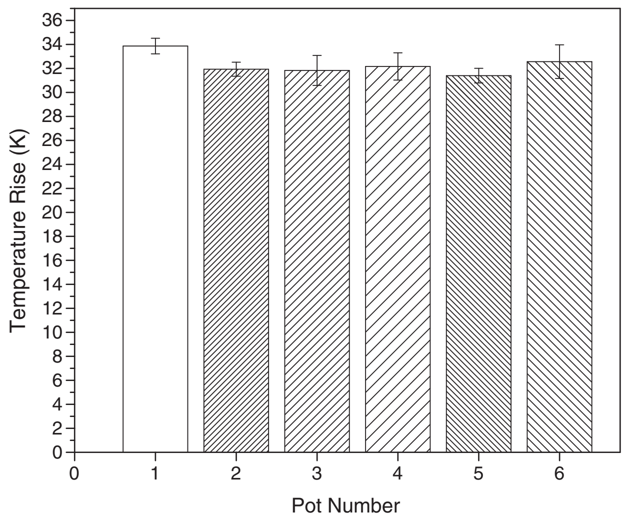

Fig. 9. Effect of pot geometry and material on heat transfer to a cooking pot. Uncertainty bars represent one standard deviation.

To determine if the repeatability of tests could be improved by limiting the impact of vaporization an experiment was conducted were vaporization was suppressed. A pot filled with 15°C ± 1 water was placed on an electric burner and allowed to heat to 90 °C. The same pot was then refilled and heated again with a piece of 2 inch thick rigid foam insulation floating on the surface. The time to heat and the mass of water vaporized was measured for each arrangement. Three test replicates were conducted.

The use of insulation reduced the total amount of vaporization and reduced the amount of variation between tests. Without insulation the coefficient of variation between tests was nearly 2% of the total energy. When insulation was used the coefficient of variation dropped nearly 4 fold to just over 0.5%.

The original VITA test procedure called for the use of a pot lid during testing but was removed during method revisions for the sake of simplicity (Bailis et al., 2007b). Although a portion of the vaporized water will contact the lid surface and condense, a large fraction will remain in the gas phase trapped between the water and lid surfaces. How tight the lid fits on the pot and the distance between the water surface and the lid will change the net vaporization which occurs. Another possibility is the heating of a fluid where vaporization is less likely to occur such as glycol or oil. The concern associated with these alternative fluids was the increased risk of burns and the fluids' low specific heats. The specific heat of most oils is less than half than that of water and glycol can be less than a quarter. With these much lower specific heats very little energy needs to be transferred to the pot before temperatures get above the point where they would be safe to use.

Experimental procedure

After considering the causes of error discussed in Section 4, a modified WBT procedure was used to explore other sources of variation. To reduce the impact of vaporization and the need for correction factors between testing locations, the temperature testing range was adjusted to 15 °C start and 90 °C finish. A layer of foam insulation was also placed on the surface of the water during the cold and hot start phases of the test to reduce variability from vaporization. The revised WBT still holds water at a constant temperature for 45 min without being covered during the simmer phase. The uncertainty associated with water vaporizing during simmer may be a concern but it is necessary to determine the low power capabilities of a stove. The uncertainty is also minimized as this is a time based test so slight variations in energy transfer are not compounded. It is felt that with lowering the simmering temperature (90 °C) and keeping a set test length, the uncertainty inherent with the test is acceptable. The simmer phase attempted to keep the temperature within ±3 °C, testers did not report having any difficulty staying within this range. As metrics of stove performance three factors were investigated; carbon monoxide (CO), particulate matter (PM), and wood use. Carbon monoxide and PM data reported represent the total masses emitted during the cold start phase of the modified WBT. Wood use is reported as the dry mass of fuel. The stove was burned in a fume hood sufficiently large to capture all the emissions of the stove with filtered inlet air to remove background particles. Background emissions levels were also accounted for. CO was measured using a Fourier Transform Infrared Spectrometer (FT-IR) and PM was isokinetically sampled onto PTFE filters (Whatman #7592-104, Maidstone, Kent UK) and gravimetrically measured. The balance used (Mettler Toledo MX5 Columbus, OH USA) had a resolution and repeatability of 1 μg. Multiple iterations of each test were conducted with the average of the tests reported. The uncertainty of each test group is reported as the standard deviation.

Parametric testing

Using the previously described test protocol, tests were conducted to determine which parameters lead to variability in test results. The goal was to determine which variables need to be controlled in the test standard and which can be allowed to vary without introducing significant uncertainty to the results. Baseline conditions were set and each test consisted of changing a single parameter from the baseline at a time. All combustion tests were conducted using an Envirofit International (Fort Collins, CO USA) model B1100 stove. A wood moisture content of 7% (dry basis) and 1.5 cm × 1.5 cm × 30 cm was used as the baseline condition. These values were set based on the moisture content which is typically achieved in Colorado from ambient conditions and geometry similar to those suggested in the WBT. The parameters tested and the number of replicates performed can be found in Table 1. Although increasing the number of test replicates conducted would be ideal, only a limited number of tests could be conducted due to resources and time. While future testing is planned, the number of test replicates conducted is similar to what current test protocols stipulate (Bailis et al., 2007b). Modifying the test protocol is useful only if the improvements are detectable at the number of test replicates which is practical to conduct during stove development.

Fuel geometry

The anisotropic nature of wood heavily affects many of its properties, including thermal conductivity, which impacts energy transfer and how pyrolysis progresses. Thermal conductivity following the grain of wood can be twice that found perpendicular to it. This difference in heat transfer rates makes a large cross-sectional area perpendicular to the fuel grain desirable to increase heat transfer. To maximize heat transfer a piece of wood should have a large cross-sectional area while also maximizing the total surface area. For a given mass, smaller pieces will have greater overall surface area while minimizing the depth heat needs to travel to the center. For geometries of equal proportions a smaller volume will always have a greater surface area to volume ratio. As the surface area of the fuel increases the radiant heat transfer from the fire back to the fuel will grow increasing the fuel consumption rate (Baldwin, 1987). Current standards in use specify 2–5 cm diameter pieces of wood to be used whenever possible.

To investigate the effects of wood geometry, experiments were conducted following the modified WBT test procedure at three fuel geometry sizes. Small (0.75 cm × 0.75 cm), medium (1.5 cm × 1.5 cm), and large (3 cm × 3 cm) were tested all with a length of 30 cm and square cross-sections. Three tests were conducted for each.

Fuel size was found to have an insignificant impact on carbon monoxide emissions (Table 2). A comparable study conducted by Bhattacharya et al. (2002) saw similar insensitivity to fuel geometry. The effect of fuel size on particulate matter production was more substantial but has large uncertainty associated with it. It was found that PM decreases with increasing wood size, although this difference was not found to be statistically significant. The cause of decreasing PM with increasing wood size may be due to the reduced number of times new wood is added to the stove. Particulate matter can be emitted both from incomplete combustion and from abrasive wear such as feeding fuel into the stove or disrupting the charcoal bed. Each time new wood is fed into the stove the partially burned wood and char is disturbed creating the potential of entraining PM into the exhaust stream (Hinds, 1999). The effect of fuel size on wood use and emissions released can be seen in Fig. 4.

Moisture content

The net calorific value available in wood is dependent on moisture content. Energy is required to heat and vaporize the moisture bound in the fuel, allowing it to reach the temperatures needed for pyrolysis and combustion to occur. The ambient moisture content a sample of wood will eventually reach is dependent on ambient temperature and relative humidity. Equilibrium moisture content of wood can vary from 1% to 25% in realistic ambient temperature and humidity conditions (Simpson and TenWolde, 2009; Van Loo and Koppejan, 2008). Moisture content and net calorific value are inversely proportional as seen in Fig. 5. Previous research has shown that although water decreases the net energy available from a biomass fuel, the presence of moisture may also slow pyrolysis reactions; increasing gas resonance time in the combustion zone improving total emissions (Baldwin, 1987).

Samples of wood at four different moisture contents were tested following the modified WBT protocol to determine the impact of fuel moisture on combustion and emissions. Moisture contents were measured using a Delmhorst J-4 handheld moisture meter. Accuracy of the moisture meter was confirmed with the oven-dry moisture measurement method. Wood was dried to 4% by being placed in an electric kiln set at 90 °C. The moisture content of two additional samples was increased to 13% and 30% respectively by being placed in a humidity controlled chamber and allowed to reach equilibrium. Before testing all samples were placed in buckets with air-tight seals and allowed to stabilize to ensure uniform moisture distribution throughout each wood piece and between all samples.

A slight increase in fuel use was found as moisture content increased from 7% to 30%. As shown in Fig. 6, as moisture content increases the total wood required to complete the task did not change dramatically. A slight decrease is seen at 7%MC but is not statistically significant when compared to any other moisture content, p-values > 0.05 (Table 3). This implies that while the net calorific value changes with moisture content the rate of energy being transferred to the pot does not. Moisture content also has an impact on the emissions released during the combustion process, although these impacts were only statistically significant for carbon monoxide ($p < 0.05$). The addition of moisture improved both CO and PM emission until the wood becomes too moist and combustion was inhibited causing a rise in gaseous and PM emissions. A study conducted by Bhattacharya et al. (2002) saw a similar trend of increasing CO with fuel moisture contents above 13%. The study unfortunately did not include tests at lower moisture contents.

Pot Geometry

The influences of pot size and shape on stove performance were explored (Fig. 9). Although, as the surface area of the pot increases heat transfer also increases, reducing the test duration and lowering fuel consumption, as shown in Fig. 7 if pot volume is held constant at 5 L the change in external surface area with diameter is small for moderately sized diameters. Within a range, the net change in surface area with changing diameter is small leading to the hypothesis that the effect of pot geometry on heat transfer will be insignificant for practical pot geometries. If no insulation was placed on the water surface the geometry of the pot would have a greater influence, as water surface area impacts heat loss and evaporation to ambient air. The thickness of the pot walls and the material the pot is constructed of both also have the potential of affecting stove performance. A heat transfer equation, Eq. (3), was used to calculate the importance of pot thickness and material on total heat flux. A basic heat flux model of convection to and from a solid with constant gas and fluid temperatures was used. Fig. 8 presents normalized heat flux plots with changing pot material conductivity. While wall thickness and pot material can vary considerably between pots the heat flux changes will be insignificant.

$$q = \frac{Tw - Tg}{\frac{1}{hg} + \frac{\Delta x}{k} + \frac{1}{hw}} \tag{3}$$

Where:

q	heat flux (W/m2)
Tg	temperature of gas below pot (T)
Tw	temperature of water in pot (T)
hg	convective heat transfer of gas, used 50 W/m^2-K
hw	convective heat transfer of water, used 2000 W/m^2-K
Δx	thickness of pot wall (m)
k	conductive heat transfer of pot material (W/m-K)

Six different pots were tested with three tests per arrangement. The dimensions and construction of the pots tested are provided in Table 4. Pots were filled with 5 kg ± 0.005 kg of 15 °C ± 2 water and heated on a propane burner for 10 min. A propane burner was used to minimize the impact of the user on the results. The mass of propane burned was determined for each test to ensure each pot was supplied with an equal amount of energy.

The temperature rise for the six pots tested were all within 2.5 °C of each other. The only pot found to have a statistical difference was pot 1 (Table 5). The tallest pots, 1 and 6, had slightly greater temperature gains then the rest. Although more tests would be required to validate, it is hypothesized this slight increase is due to their greater heights. The additional material may have improved heat transfer to the water, behaving similarly to a heat fin.

Modified testing protocol

After reviewing the testing standards for biomass cookstoves currently in use it was decided to create a hybrid of the protocols. The goal was to achieve a test which captured the best of each test while addressing some concerns surrounding the existing methods. The proposed protocol relies on a task based test while better controlling variability in energy transfer.

To test the collective impacts of the modified WBT a series of tests were conducted and compared against the standard WBT. The procedure outlined in Section 5 was used holding fuel moisture content at 7% (dry basis), the medium fuel geometry, and pot 1 consistent, here after the modified WBT will be called the Emissions and Performance Test Protocol (EPTP). Three EPTP replicates were conducted on the Envirofit International B1100 cookstove and compared to standard WBT tests conducted on the same stove prior to this research. Dry fuel use and CO emissions were compared. Particulate matter is not being compared as modifications to the PM sampling system occurred between the two data sets.

Fuel required to complete the simmer phase of the tests was the only metric found to have statistical significance ($p \leq 0.05$) (Table 6). A comparison of the average values from three test replicates following the standard and modified WBT methods can be found in Fig. 10. Although the differences are not significant, it appears that changing from the WBT to EPTP might alter the amount of CO emitted. It is thought that these differences may be an artifact of the limited number of test replicates conducted but additional test replicates and similar studies conducted on other biomass stove designs will be required to determine conclusively.

The goal of the EPTP was to reduce variability in testing results. The EPTP was found to reduce the coefficient of variation (COV) for nearly every stove performance metric tested. A comparison of COV results can be found in Fig. 11. From these results it can be seen that the EPTP achieves its intended goal, decreasing the uncertainty associated with testing biomass cookstoves while still remaining a practical and feasible test protocol. It will be up to the groups testing biomass cookstoves to determine if the reductions in variation seen with the EPTP are great enough to justify changing the status quo.

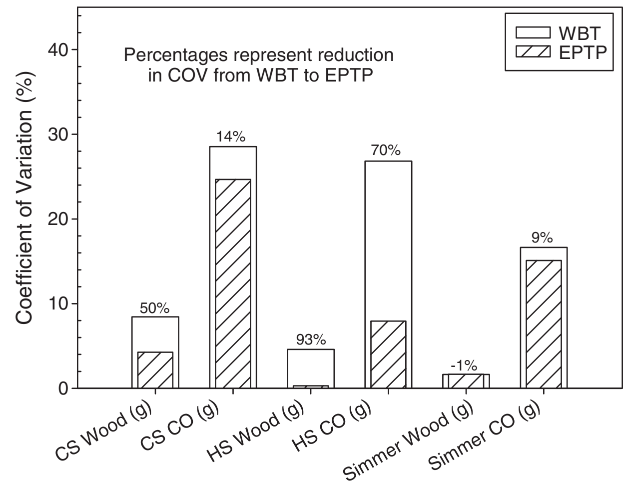

Fig. 11. Coefficients of variation following the WBT and EPTP Methods.

Conclusions

Biomass combustion is a complex process which has variability inherent in its nature but many of the concerns can be addressed. By understanding the chemical and physical reactions which are occurring during biomass combustion a test protocol can be developed which allows for a task based test while still controlling energy transfer. By adjusting the water temperature testing range it becomes possible to reduce the influence of local boiling temperature and variable vaporization. With the addition of a simple insulative layer on the surface of the water test variability can be further reduced by limiting the impacts of vaporization.

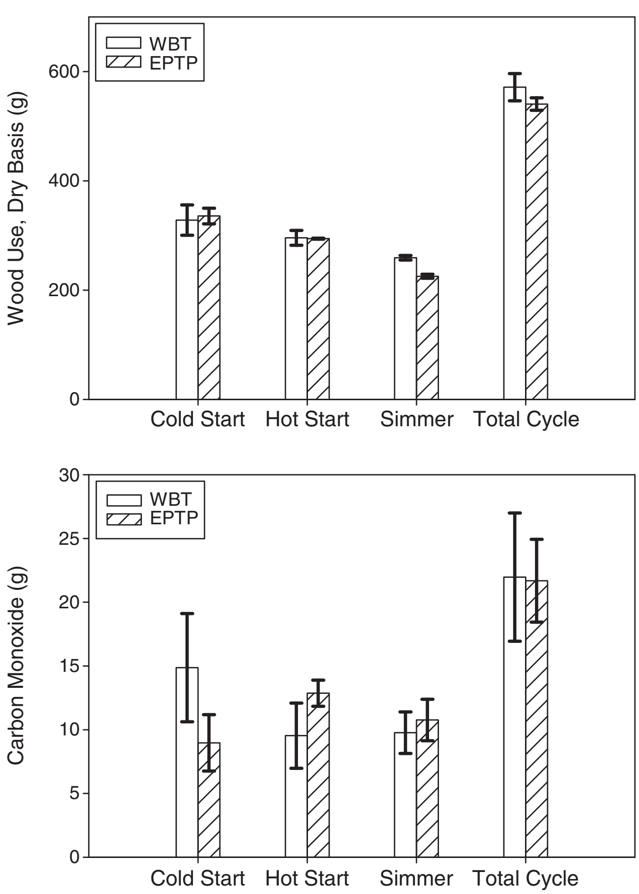

Fig. 10. Stove performance following the WBT and EPTP Tests. Uncertainty bars represent one standard deviation.

Using a robust test protocol it becomes possible to explore the influence of test parameters on stove performance and repeatability. It was found that while some test parameters need to be controlled for repeatability many do not allowing for a more practically conducted test. It was found that while the moisture content of the fuel has a significant effect on performance fuel and pot geometry do not. Based on these results it is suggested that while general guidelines for fuel shape and pot geometry should be specified rigid standards are not required. Although only a limited selection of cooking pots was available for testing, results and heat transfer theory led the authors to feel comfortable in accepting the assumption that any pot capable of holding the required amount of water of a size roughly 25 cm in diameter will perform similarly. The material and thickness of the pot walls have the potential to change heat transfer from the stove but most readily available pots constructed of aluminum or stainless steel are deemed to be acceptable. Slight variations in fuel geometry are not expected to cause significant discrepancies between tests but if fuel is being cut to size it should run with the wood grain and have a diameter of 1–5 cm. Fuel moisture content needs to be standardized for test results to be comparable with any accuracy. While 7% moisture content was used during the parametric testing, that moisture content does not have any special significance but standardized moisture content does need to be established. In theory there is nothing preventing the use of the suggested protocol in any situation but it is recognized that the ability of sticking to a specific fuel moisture content can be most easily achieved in laboratory situations. Validation of the proposed protocol would also benefit from future testing being done using a variety of biomass cookstoves.

There will be times when it is necessary to make adaptations to the testing protocol. The same test procedure can be used for many testing conditions with slight modifications to accommodate the stoves to be tested. For example 5 kg of water may not be appropriate for some stoves. A large industrial stove will not often be heating only 5 L. 5 kg of water will be appropriate for most stoves designed for family use but it is important to match the water mass to stove firepower. Modifications to the protocol may also be required based on stove design. A batch fed or gasifier stove may not be able to adhere to the guidelines on fuel geometry.

There are some test factors which have not been tested here such as ambient temperature and fuel species used as they have been considered secondary test factors here. The ambient temperature of the test facility has the potential to change the combustion process and heat transfer from a stove. While the influence of temperature needs to be explored in the future it was decided that the variation of roughly

50 °C which could be seen between testing locations is insignificant when compared against the variations of more than 800 °C expected in the combustion zone. The wood species used is often dependent on the location of testing but despite the fact that physical properties of wood, such as density, vary significantly with species the energy content per unit mass is similar (Tillman et al., 1981).

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