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Estimation of transient thermal efficiency of a biomass cookstove

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ABSTRACT

Biomass cookstoves are used by many people throughout the developing world for daily cooking, which unfortunately brings inherent risks to individuals and the environment. During the past several decades, extensive efforts have been made to mitigate the harm by developing clean burning, high efficiency biomass cookstoves. However, comparison and selection of cookstoves has proven to be difficult. Generally, cookstoves are characterized using the Water Boiling Test (WBT) or a variant thereof. The WBT protocol identifies several metrics used to assess cookstoves, such as average thermal efficiency (η_{avg}), turn-down ratio, time to boil, and several pollutant-based metrics. Unfortunately, the results of lab tests often are not replicated by actual users in the field. Additionally, results may vary from lab to lab and sometimes within the same lab. To provide an additional tool for assessment, this study demonstrates how to predict a cookstove's average thermal efficiency with time (η_t) which enables analyses and comparisons not possible using η_{avg} obtained at the end of the WBT. Model predictions were validated with several experiments. Insights and benefits of time-dependent η_t analysis include reduced testing times, identification of the reasons η_{avg} varies in repeated experiments, comparison of η_t at specified times even when the length of tests differ, identification of η_t characteristics between cold and hot starts, and determination as to if and when η_{avg} has reached steady state. The only required modification of the current WBT protocol to obtain η_t is to record water temperature with time.

Introduction

Biomass cookstoves are commonly used for cooking throughout the developing world. Unfortunately, use of biomass cookstoves creates emissions that can be hazardous to users and the environment. These emissions increase the threat of asthma, release cancer causing agents and can lead to carbon monoxide poisoning (Mueller et al., 2011; Chowdhury, 2012; Abeliotis and Pakula, 2013; Hawley and Volckens, 2013). The environmental effects of these cookstoves range from release of gases that contribute to climate change to release of particulate matter that may have an effect on glacial melting (Bond et al., 2013).

These issues with biomass cookstoves have been the impetus for continually growing efforts to improve cookstoves. This effort has produced a large number of well-engineered cookstoves, but comparison and selection continues to be an issue (Jetter and Kariher, 2009; MacCarty et al., 2010). Many cookstoves are built with different purposes in mind, such as cooking a stew vs. cooking a flatbread. Other cookstoves use different kinds of fuel, including wood, leaves, or dung. Compounding these issues is that the metrics that are important in comparing cookstoves are not completely settled or characterized (Taylor, 2009; Kshirsagar and Kalamkar, 2014). Some of the metrics that have been used in cookstove comparison and selection have included thermal efficiency, fuel economy, emissions, and high and low power fuel rates (Taylor, 2009; Jetter et al., 2012). These metrics may or may not be comparable for stoves of different feeding rates, fuel types, etc. and so it is important to understand how various experimental parameters affect the performance metric used for comparison.

One of the most commonly used metrics is that of thermal efficiency. Average thermal efficiency (η_{avg}) typically obtained at the end of a cookstove test is defined as the total amount of heat that goes into the water in the pot divided by the total heat potentially available to the pot during the test. There are many challenges associated with using η_{avg} as a metric for comparing biomass cookstoves. Some of these challenges originate from the fact that all the data points that are used in its calculation are based on measurements taken at the beginning and end of the test and so they provide an average efficiency over the course of the whole test. Unfortunately, not every test uses the same endpoints.

Assessment of η_{avg} is typically obtained using the Water Boiling Test (WBT) (MacCarty et al., 2010; Jetter et al., 2012; Manoj et al., 2013; Bailis et al., 2014; Kshirsagar and Kalamkar, 2014). While the WBT protocol calls for the water to actually boil, some researchers prefer to finish tests at 90 °C (Defoort et al., 2009; Bailis et al., 2014). How η_{avg} depends

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on the methods used within the protocol or how fire placement affects η_{avg} during the course of the experiment is not yet fully defined. For instance, η_{avg} may be effectively evaluated long before boiling occurs, which would significantly reduce the time required to test a stove. In addition, differences between a cold start analysis and a hot start analysis of the WBT need to be quantified more rigorously. The cookstove is at ambient temperature at the beginning of a cold start test and a hot start test begins soon after a cold start test while the cookstove is at a temperature above the ambient temperature. The designers of the WBT are aware of the many challenges inherent in the current testing protocol and caution in the use of its results is warranted (Bailis et al., 2014).

The objective of this paper is to demonstrate that analysis of the time-dependent behavior of η_{avg} (denoted as η_t) overcomes some of these challenges and enables comparison of results of tests with different endpoints. Additionally, η_t measurements obtained during cold and hot starts provide significant insights.

Materials and methods

Testing chamber and cookstove

A modified Peruvian-style channel cookstove was used for all tests as shown in Fig. 1. The Peruvian-style channel cookstove in its most basic form is simply two rows of bricks stacked parallel to each other. The cookstove used in these experiments included a grate between the first and second layer of bricks and a pot skirt (see Fig. 1). The brick walls used in this cookstove were 3.5 bricks high and 2.5 bricks long, which resulted in a wall 19.5 cm tall by 56 cm long and 10 cm wide.

This cookstove was placed inside a cinderblock structure that was built on a metal cart. The cinderblock structure measured 1.4 m long, 0.8 m wide, and 0.7 m tall. Within the cinderblock structure, the cookstove was placed on a 6.4 mm thick metal plate that was placed on a 10 cm deep container of sand. The container of sand was used to simulate typical conditions in which the cookstove is on the ground. An exhaust hood was attached to the top of cinderblock structure. The flue and exhaust hood fan combined to give the hood a flow rate of approximately 16 l/min.

Experimental protocol

The WBT protocol (Bailis et al., 2014) was followed and the measured values were used to calculate η_{avg}. The wood used in these experiments was Douglas fir cut into 2 cm × 2 cm × 25 cm uniform sticks. The wood was dried in a dehydrator for approximately 24 h before testing to minimize the moisture content. The moisture content was consistently below the detectable limit of 5% (dry basis) for all experiments as measured using a General Tools wood moisture meter (MMD4E The Seeker, General Tools, New York City, NY). The water was placed in a 25-cm high by 25-cm diameter (15 l) pot. Four cold-start experiments were conducted in which the pot was initially filled with 2.5 l of water. Three hot-start experiments were conducted in which the pot was initially filled with 2.5 l of water whereas the remaining four hot-starts were conducted using 5.0 l of water. The difference in water volume was used to assess its impact on η_{avg}. The temperature of the water was measured every 2 s using a k-type thermocouple.

A log-cabin configuration of wood was used at the beginning of each test to start the fire (Fig. 1b). The log-cabin structure was formed from four layers of two sticks where the sticks were half of the original length. Small pieces of wood and some torn newspaper were placed in the middle of the log cabin as a starter. Once the fire was started, full-length sticks were added at four-minute intervals. Bundles of two and three sticks were alternately added to the fire, and this pattern continued throughout the experiment. Some experiments ended when the water reached a particular state (90 °C, boiling, etc.) and others ended at a specified time. At the end of the test, the fire was pulled out from within the cookstove and smothered. The masses of the remaining wood and charcoal (both in the chamber and removed from charred wood) were weighed using a digital scale with an accuracy of ±0.5 g. Both the cold start and hot start experiments used this method, with an additional requirement that the hot start be started immediately following another experiment.

Estimation of average thermal efficiency (η_{avg}) with time

The thermal efficiency (η)of a biomass cookstove is given by

$$\eta = \frac{E_{pot}}{E_{fuel}} = \frac{Cp_w * m_{water,i} * \Delta T + \Delta h_{H2O,fg} * \Delta m_{water}}{f_{cm} * (1-MC) * LHV_{wood} - f_{cm} * MC * y * LHV_{wood} - LHV_c * m_c} \quad (1)$$

where E_{pot} is the heat transferred to the water in the pot and E_{fuel} is the energy available to the pot. For the WBT, the measured parameters in Eq. (1) are recorded at the beginning and end of the test leading to an average thermal efficiency for the entire test where $\eta = \eta_{avg}$. Note that Eq. (1) does not differ from the expression originally used in the

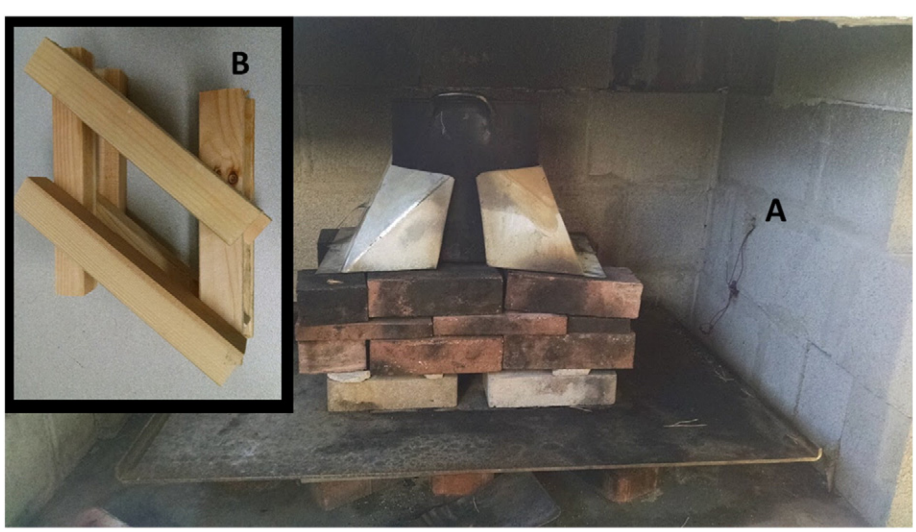

Fig. 1. (A) Cookstove testing chamber with a traditional Peruvian brick channel cookstove resting atop a metal plate. A skirt surrounds the pot that sits on top of the stove. The cookstove is placed in a hood vented to a chimney that is augmented by a fan. (B) The wood is arranged in a 'log-cabin' configuration made of sticks measuring 2 cm × 2 cm × 13 cm. There are 4 layers of sticks, with each layer containing 2 sticks.

WBT protocol as it is only a rearrangement of terms (Bailis et al., 2014). The two terms in the numerator represent the sensible and latent heat transferred to the water. Here, Cp_w is the heat capacity of water at 100 °C, $m_{water,i}$ is the initial mass of water, ΔT is the change in temperature over the course of the test, $\Delta h_{H2O,fg}$ is the heat of vaporization at the ambient pressure (assumed to be one atmosphere), and Δm_{water} is the mass of the water that was vaporized during the test. The three terms in the denominator represent the energy in the dry wood that is used, the energy needed to remove moisture from the wood, and the energy remaining in the charcoal after the burn. The latter two terms are subtracted from the first term so that E_{fuel} represents the available energy. Here, f_{cm} is the mass of the fuel consumed during the test, MC is the initial percent moisture of the wood, LHV_{wood} is the lower heating value of the wood, LHV_c is the lower heating value of the char from the wood, m_c is the mass of char remaining at the end of the test, and y is a factor to account for the energy lost to evaporation of the moisture in the wood, which is defined as,

$$y = \frac{\left[Cp_w * (T_{boil} - T_{amb}) + \Delta h_{H_2O,fg}\right]}{LHV_{wood}} \tag{2}$$

where T_{boil} is the boiling temperature at one atmosphere of pressure and T_{amb} is the ambient temperature.

While most of the terms in these equations stay constant throughout the experiment, to calculate η_t (the time-dependent average) there are four terms in Eq. (1) that need to be measured or calculated as functions of time. The four terms are ΔT, Δm_{water}, f_{cm}, and m_c. The initial moisture content of the wood, p_m, also varies with time. However, the wood is initially well dried, so variations in p_m are neglected. Of these four terms, ΔT, f_{cm}, and m_c are simple to measure or approximate with time. A thermocouple can be used to measure the temperature at any time, so ΔT can be measured at any time. In contrast, total f_{cm} and m_c are measured at the end of the test and it was assumed that these parameters varied linearly with time since an approximately constant consumption of wood (f_{cm}) could be observed from data (Bussman, 1988) in previous studies, even with wood added in batches throughout the experiment.

The key to the analysis of η_t is the temperature data taken during each experiment. The thermocouples used were k-type thermocouples with data points taken every 2 s. To estimate Δm_{water} with time, a mass balance of the water on the pot was used since the only data obtained was Δm_{water} at the end of the experiment, which is typical of the WBT. The mass balance for water, assuming a well-mixed system, is

$$\frac{dm}{dt} = -k \cdot A \cdot \left(P_w^s - P_w^a\right) \tag{3}$$

where m is the mass of water in the pot, t is time, k is the mass transfer coefficient characterizing water loss from the pot based on a partial pressure driving force, A is the surface area of the water exposed to the atmosphere, P_w^s is the partial pressure of water vapor at the water surface, and P_w^a is the partial pressure of water in the atmosphere which is associated with the humidity. P_w^s can be approximated using Raoult's Law which shows that $P_w^s = x_i P_i^*$ where x_i is the mole fraction of water in solution (which is unity) and P_i^* is the vapor pressure of water at its current temperature. Thus, P_w^s is equivalent to P_i^* evaluated at the water surface temperature. For this study, the surface temperature was approximated to be equal to the temperature of water in the pot (which changes with time). P_w^a, which is constant, was obtained from relative humidity data at the ambient temperature.

Assuming a constant time-averaged value of k, integrating Eq. (3) gives

$$\Delta m_{water} = k \cdot A \int_0^t \left(P_w^s - P_w^a\right) dt \tag{4}$$

Over the course of the entire experiment, the temperature of the water is measured with time. Therefore, P_w^s at each temperature can be calculated from the Riedel Equation (Riedel, 1954; Sandler, 2006; Vetere, 2006) and therefore $(P_w^s - P_w^a)$ as a function of time can be generated. The time-averaged value of k is then obtained by dividing the measured Δm_{water} at the end of the experiment by the water surface area and the area under the $(P_w^s - P_w^a)$ curve. Once k is determined, $\int_0^t (P_w^s - P_w^a) dt$ may be evaluated at any time such that Eq. (4) then provides an estimate of Δm_{water} at any time. Now that the four terms, ΔT, Δm_{water}, f_{cm}, and m_c, are either measured or estimated as functions of time, η_t is determined using Eq. (1). The results and discussion section provide details regarding the validation of this approach.

Results and discussion

Table 1 shows a summary of measured and calculated values for each cold start (CS), hot start (HS), and validation (VAL) experiment. As can be seen, there was variation in the tests. Some of this variation was controlled during the experiment ($m_{water,i}$, ΔT, Final T, and whether boiling occurred) and some variation (Δm_{water}, %lost, and η_{avg}) was a consequence of the testing process. For instance, the percent of the initial water that was lost during the experiment (due to vaporization or boiling) ranged from 1.1% to 24.8%. Similarly, there was a wide range in ΔT from 21.1 to 72.7 K. These types of uncontrolled or controlled variations can lead to variations in η_{avg}. This leads to the question as to whether η_{avg} can be compared between tests when such variations occur. For instance, the CS experiments showed η_{avg} varying from 11 to 17%. In the literature, there is also a fair amount of variation in cookstove testing between different types of cookstoves. The remaining results demonstrate how η_t can be assessed, resulting in valuable insights when comparing cookstove tests even in the presence of uncontrolled or controlled variations with varying test endpoints.

The time-dependent temperature profile (solid line) shown in Fig. 2 (from CS2) is representative of the measured temperature profiles for cold start tests. The water temperature was measured every 2 s. Each experiment showed similar trends. There is a short lag time at the beginning of the experiment where the fire has not reached its steady-state burning. Once the fire begins to approach a steady burning rate, the water heats up in a nearly linear manner until it approaches the boiling temperature. As it approaches the boiling temperature, the rate at which water evaporates increases, and the rate at which the temperature of the water changes decreases. When the experiment reaches the boiling temperature, the water temperature stays constant as expected.

Fig. 2 also shows the prediction of η_t for CS2. The figure includes total η_t (dashes and dots), the portion of η_t resulting from water heating which is the first term in the numerator of Eq. (1) (dots), and the

Table 1
Summary of measured and calculated values for each experiment.

Test	Controlled parameters				Uncontrolled parameters		
	$m_{water,i}$ (g)	ΔT (K)	Final T (°C)	Boiled	Δm_{water} (g)	% lost	η_{avg} (%)
CS1	2468	21.1	94.8	Y	611	24.8	16.5
CS2	2505	72.7	95.0	Y	319	12.8	15.5
CS3	2490	64	90.9	N	87	3.5	14.3
CS4	2449	69.2	90.2	N	144	5.9	11.3
HS1	4910	68.2	89.8	N	144	2.9	18.5
HS2	4916	71.4	91.2	N	172	3.5	17.6
HS3	4943	69.9	90.4	N	156	3.2	16.3
VAL1	2524	35.5	62.2	N	40	1.6	15.2
VAL2	2492	71.5	94.3	Y	125	5.0	18.0
VAL3	2481	70.5	94.9	Y	351	14.2	16.7
VAL4	4918	41	63.7	N	55	1.1	17.2

$m_{water,i}$ is the mass of initial water in the pot, Δm_{water} is the mass lost over the course of the experiment, % lost is the percent of the initial mass that was lost over the course of the experiment, ΔT is the temperature difference from the beginning to the end of the test, final T is the temperature of the water at the end of the test, the boiled column indicates whether or not the water boiled during the test, and η_{avg} is the average thermal efficiency at the end of the test.

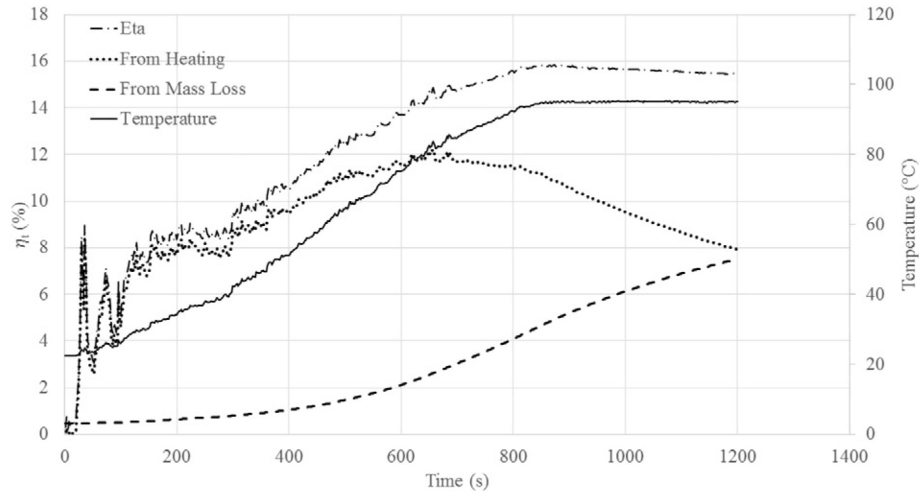

Fig. 2. Temperature and efficiency with time of water in the pot for a cold start (CS4). This data is from an individual cold start that reached boiling. Included are the temperature profile (solid line), total efficiency (alternating dashes and dots), efficiency due to temperature increase (dotted line), and efficiency due to water evaporation (dashed line). η_t was calculated based on Eq. (1).

portion of η_t resulting from water loss through vaporization which is the second term in the numerator of Eq. (1) (short dashes). As expected, η_t associated with water vaporization becomes more important as the water temperature approaches the boiling point due to the non-linear effect of vapor pressure with temperature. With this non-linear effect, Δm_{water} increases non-linearly according to Eq. (4). The distinction between the total η_t and the η_t due to water heating increases significantly as the water heats up. The percentage of η_t due to water evaporation reaches a value near 50% at the end of the experiment shown. Early on (before 400 s with this study), the percentage of η_t due to water evaporation is below 10% such that its contribution is not as critical during the early stages. The contribution due to water heating (middle line) decreases near boiling since the ΔT term in the numerator of Eq. (1) remains constant while the denominator continues to increase due to the burning of wood. The distinction of η_t information in Fig. 2 is valuable, especially when seeking to compare results from studies in which the pot was covered with studies in which the pot was uncovered. For instance, having a lid will decrease the contribution associated with water vaporization, but it is unclear how the total η_t would be affected. Comparisons will be more applicable if η_t information is available since η_{avg} provides less comparison information.

The *k* values calculated for the experiments of this study are shown in Fig. 3. The values of *k* are shown according to experiments where the water did not reach the boiling temperature by the end of the experiment and where the water did reach the boiling temperature. As is evident, *k* values are very consistent among the non-boiling experiments (except two values, VAL1 and VAL4, that are nearly three times as high as the other values) and similarly consistent, but different, among the boiling experiments. For VAL1 and VAL4, these studies stopped at a much lower ending temperature (~63 °C) than the other non-boiling experiments (ending above 90 °C) and a plausible explanation and analysis is presented in the discussion section. With removal of these two high values, the averages and standard deviations of the non-boiling and boiling experimental k values were 0.9 ± 0.1 and 1.3 ± 0.2 mg m^{-2} Pa^{-1} min^{-1}, respectively. These values are statistically different at the 99% confidence level. It was expected that boiling studies would have slightly higher *k* values than the non-boiling studies since boiling can increase the time-averaged mass transfer coefficient. An

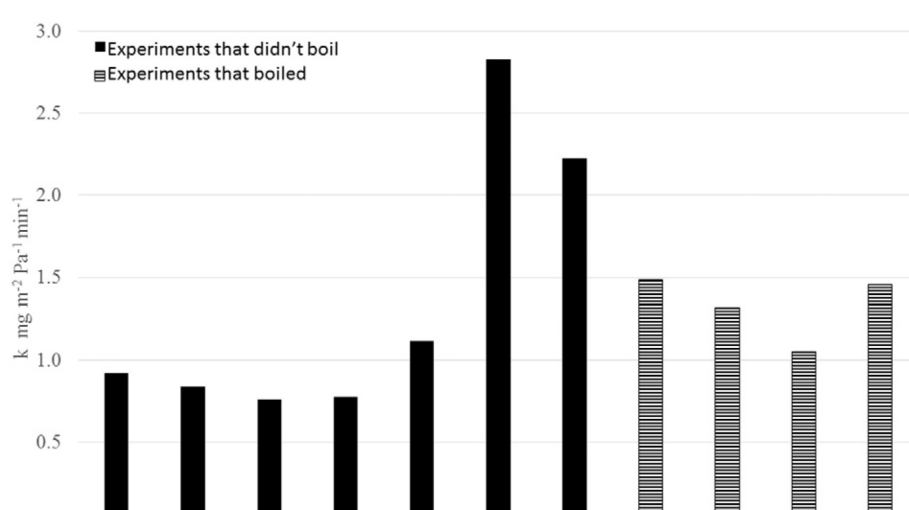

Fig. 3. Mass transfer coefficients (*k*) calculated for each experiment which characterizes water lost from the post. Values of *k* were calculated using Eq. (4). The *k*-values are separated into non-boiling (solid bars) and boiling (horizontally-lined bars).

increased value of k due to boiling can over predict Δm_{water} with time during the early stages of the experiment. However, this over prediction would minimally impact η_t predictions since, as previously shown in Fig. 3, the η_t term related to water mass loss is a small fraction (<10%) of η_t during the initial stages of water heating. It should be noted that the k values were consistent even when the time and type (hot start vs cold start and 2.5 l vs 5.0 l) of experiments varied, further demonstrating the validity in estimating k values for Δm_{water} predictions with time.

Fig. 4 shows the prediction of η_t for the three hot starts (HS1, HS2, and HS3) having 5 l of water in the pot. The standard deviations shown at the end of the run are based on propagated error analysis (Bethea and Rhinehart, 1991). The general shape of η_t for these experiments shows a slight delay (30 s or less) followed by a steep increase that levels out to a constant value. All hot start tests showed that η_t reached near-steady state at close to 400 s into the experiment, however before that time there is significant noise in the prediction because of minor variations in the temperature reading. At the end of the test, the hot start replicates reached an average η_t value of 17.6% (standard deviation of 1.4%) which is equivalent to η_{avg} that would be obtained with the WBT.

In addition, four η_{avg} values were calculated for three hot starts (VAL1, VAL2, and VAL3) using 2.5 l of water and one hot start (VAL4) using 5.0 L of water to validate the predictions of η_t. η_{avg} does not require any predictions with time so a k value is not needed. The error bars are also based on the same propagated error analysis noted above. As shown, the η_{avg} for all validation experiments were within the range of η_t predictions for the hot starts. Although not part of this study, the validation experiments showed that water amount may not be significant for hot start analysis although further experiments need to be conducted to assess this finding. On another note, and referring back to Fig. 3, both outlier k values (VAL1 and VAL4) were obtained when the experiment stopped long before boiling. Fortunately, since k is only used to predict Δm_{water} with time and that this term in Eq. (1) is not significant early in an experiment due to little vaporization, the η_{avg} for VAL1 and VAL4 agrees well with the time predicted η_t for the longer hot start studies.

From the hot start studies, two significant conclusions were identified. First, the predictions for η_t at a given time were consistent with values of η_{avg} which validates the time predictions. Second, η_t leveled off very early in the experiment (at about 7 min where the water temperature was ~63 °C) such that the η_{avg}, typical of the WBT, can be predicted long before boiling.

Fig. 5 shows the results of four cold starts (CS1, CS2, CS3, and CS4) having 2.5 l of water in the pot. Two of the four cold starts (CS3 and CS4) have significantly different ending points compared to the two cold starts (CS1 and CS2) where η_{avg} is similar to η_{avg} of the hot starts. However, η_t increases more rapidly for hot starts than for cold starts. If CS1 and CS2 had been stopped much earlier, the η_{avg} would be much lower than the hot start η_{avg}. Thus, if cold start and hot start η_{avg} data is averaged to evaluate stove η_{avg}, it is important that cold starts are run long enough.

Interestingly, CS3 and CS4 show η_t data that are different from CS1 and CS2, the latter which approach the hot start η_t at the end of the experiment. One of the cold starts (CS4) has similar η_t behavior as CS1 and CS2 until 500 s and then the η_t essentially levels off at approximately 12%. If only average analysis was performed, an erroneous conclusion could be that the CS4 test was completely different than CS1 and CS2. With η_t data, the additional information shows that CS4 was similar to CS1 and CS2 and then something happened experimentally to change the behavior of the stove. When the temperature profile from CS4 was investigated, it was found that there were two distinct linearly increasing temperature regions. The first region had a slope very close to that of CS1 and CS2, while the slope of the second region decreased to about half of that rate. This indicates that heating to the pot was significantly disrupted at this point, perhaps due to some disruption in the fire pattern. Video recordings at this time point could help identify possible reasons. Thus, η_t analysis can provide important insights to help understand deviations in η_{avg} so that erroneous conclusions do not occur.

Similarly, CS3 had a significant delay in η_t but it can be seen that the η_t starts approaching the η_t of CS1 and CS2 at later times. Thus, depending upon when an experiment stops, η_{avg} may seem the same or different. Again, the above analysis points to the value of estimating transient η_t data. As can be seen, the cold start data is significantly less consistent among the four experiments but η_t analysis provides some clarity for comparison.

To obtain η_t predictions, two key assumptions were made. First, it was assumed that the k value in Eq. (4) was independent of time. As previously discussed with Fig. 3, the difference in k values between the experiments that ended at 90 °C and those that boiled was expected although the variations in k likely did not affect η_t predictions. However, the two high k values for the non-boiling studies were not expected. Interestingly, these two high k values were obtained for the experiments that stopped at 63 °C, far below the boiling temperature. One hypothesis that was explored was the potential of a thermal boundary layer forming around the sides of the pot due to the skirt increasing the

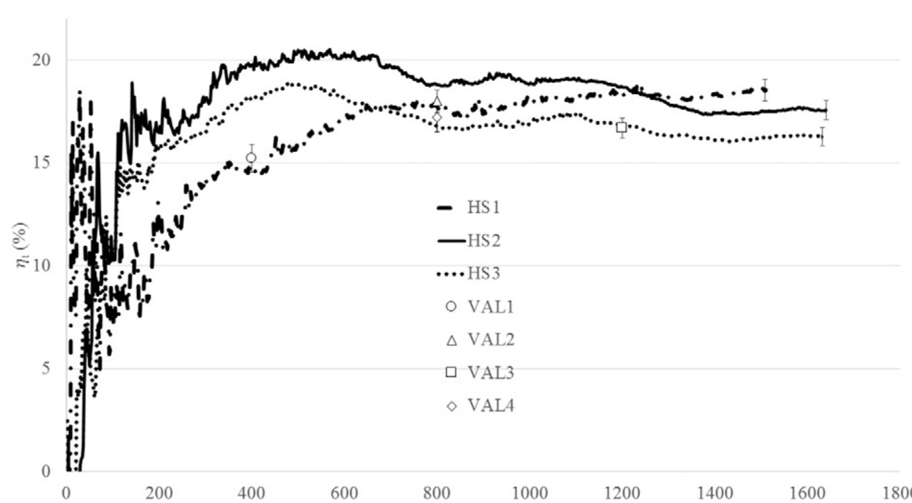

Fig. 4. Average thermal efficiency (η_t) predictions with time and validation experiments for hot starts. Each hot start is represented by a line, while the four validation runs are represented by symbols. The standard deviations of each experiment are based on propagated error analysis (Bethea and Rhinehart, 1991).

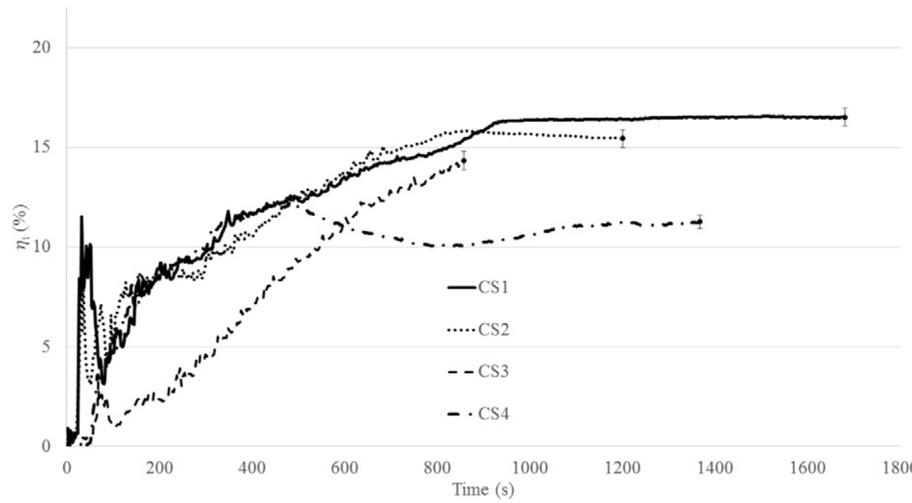

Fig. 5. Average thermal efficiency (η_t) predictions with time and validation experiments for cold starts. The standard deviations of each experiment are based on propagated error analysis (Bethea and Rhinehart, 1991).

heat transfer rate to the walls of the pot. The increased temperature of the water at the wall relative to the bulk temperature would result in a higher effective P_w^s than predicted by just using the bulk temperature- this effect would be more pronounced at lower temperatures. A higher P_w^s would lead to a lower prediction for k. However, subsequent analysis by measuring temperature profiles near the wall showed that the boundary layer was too small to fully justify this reasoning.

Although the k predictions were higher at 63 °C, the effect of Δm_{water} predictions for estimating η_t are not as critical for experiments at these temperatures which stop far below the boiling point since the value of Δm_{water} on η_t has a smaller effect. As shown in Fig. 2, the fraction of η_t attributed to Δm_{water} (noted as mass loss in the figure) is 11.2% at 63 °C whereas the fraction increases to 30% at boiling and further to 48.6% by the end of the test. Similarly, in Fig. 4, η_{avg} taken at 63 °C (VAL 1 and VAL 4) showed good agreement with η_t predictions. This again shows that the effect of Δm_{water} predictions at the lower temperatures do not contribute as strongly to the prediction of η_t. Therefore, while the predicted η_t curves are based on several assumptions, the general trends are not largely affected by perturbations in the assumptions nor in the variability of k values obtained from ending at significantly lower temperatures.

The second key assumption in predicting η_t is the linear nature of the wood mass loss (f_{cm}) and charcoal formation (m_c) used in Eq. (1). In the early 1980s, a group at the University of Eindhoven conducted a series of experiments on biomass cookstoves, including some experiments in which the fuel bed was placed on a balance (Bussman, 1988). A graph of the mass of the cookstove with time showed that the mass loss with time was approximately linear even when the wood was added at various intervals during the study. It also showed an approximately linear increase in coal formation. This supports the idea that both the mass loss and the charcoal creation can be approximated as linear for η_t predictions when the feeding rate is consistent.

As shown in Fig. 5, there is value in estimating η_t. This was most evident with the cold start data where for two of the experiments the η_t was either delayed (CS3) or unexpectedly suppressed (CS4). These observations could only be determined with predictions of η_t and it is clear that such predictions can help understand η_{avg} deviations within testing of the same cookstove or can also help provide insights when comparing between cookstoves. Unlike η_{avg} analysis, which is the norm for the WBT, trends in η_t analysis can provide insights into testing protocols even when testing parameters vary as much as shown in Table 1. For instance, for the hot start studies η_t began to level off between 400 and 500 s into the experiment. This corresponded to a ΔT of between 20 and 30 °C, meaning that η_t stabilized by the time that the originally 20 °C water has reached somewhere between 40 and 50 °C. This is significantly below the boiling time. Some question has arisen as to whether the WBT should go to boiling or not (Defoort et al., 2009; Bailis et al., 2014) and this study supports the idea that one could stop the WBT long before boiling occurs during a hot start. This could potentially decrease the amount of time and wood required for each experiment significantly when emissions data is not being used or collected.

Shortening the cold start phase, however, may not be as feasible. As was shown in Fig. 5, the cold start phase reached steady state η_t much later than the hot start phase. In fact, when using 2.5 l of water for this cookstove during the cold start, the steady state η_t didn't occur until just before boiling occurred. Therefore, to more fully capture the cold start phase it may be best to run a long test that boils for at least some time or use larger quantities of water. Because of this finding, when testing cookstoves it may be desirable to perform one cold start followed by several hot starts. The performance of more than one hot start following a cold start phase and preceding the simmer phase, which is different than the WBT protocol, lends itself to several advantages. First, it allows for more consistent data to be obtained in a shorter time. A cold start requires a cold stove, and so once a test is performed it is necessary to wait until the stove has cooled to begin anew. A hot start, however, should be able to be repeated one after another without significantly affecting η_t as shown in this study. This leads to a better statistical analysis. It is important to note that the hot start and cold start phases should have a similar final η_t (which is equivalent to η_{avg} from the WBT) for experiments that achieve steady state efficiency. This is consistent with other observations as the percent of heat loss to the cookstove body has been observed to be low (Tryner et al., 2014). Second, the current method of the WBT does not measure the charcoal remaining at the end of the hot start phase. Instead, the charcoal remaining is assumed to be the same as the preceding cold start phase. If multiple hot starts are performed, the charcoal remaining from all of the hot starts except for the last one can be measured. Combining this with the fact that hot starts may be able to be shortened significantly would lead to a greater amount of data for statistical purposes.

On another note, many styles of cooking that have been tested in the field require a longer cooking time than is required to accomplish the WBT tasks (Commodore, et al., 1994; Chowdhury, 2012), and so η_{avg} may be closest to what happens in the field for long cooking times. However, the ability to predict η_t would allow for η_{avg} to be estimated for shorter cooking styles, increasing the versatility of the comparison to field use. The WBT currently attempts to more closely approximate field use by having different phases. The typical WBT includes a cold start, hot start, and simmer phase in order to approximate cooking on a cooled stove, cooking on a hot stove (e.g. cooking a meal soon after finishing another), and the cooking of foods that require a long time such as legumes. These phases help to close the gap between lab testing and field testing performance, but the challenges with this comparison are well documented (Taylor, 2009; Bailis et al., 2014). It is therefore important to know when to stop a test.

Any cookstove will have some transient time before it reaches its steady state η_t. To maximize the amount of information gathered in any individual test it is important that η_t approaches steady state as much as possible by the end of the test. Using the data from Fig. 5, it is clear that this can require different times for cold and hot start phases. A stove with a high thermal mass will also require more time to reach a steady state η_t than a stove with low thermal mass. The cold start phase curve of the η_t for a stove with extremely low thermal mass should approach the hot start phase curve. One way to estimate the minimum time required to reach steady state η_t would be to run a test until the water is in a rolling boil state for both the cold start and hot start phases and graph η_t with time. This would allow the researcher to see the whole curve and make a determination based off of that information. However, the results of this study also suggest that at least for the hot start phase this time could be significantly reduced. It is possible that the high thermal mass of this stove is the cause of the longer length of time required to reach the steady state η_t for the cold start. If this is true, then a lighter stove should reach its steady state efficiency more quickly for a cold start and so the 30 °C temperature rise required for the hot starts observed in Fig. 5 should also be sufficient for a cold start. Predicting η_t can provide insights needed for adjusting protocols and comparing cookstoves with varying protocols. It is also recommended that once a final time or temperature has been selected, predicting η_t will allow one to confirm whether or not η_{avg} has stopped changing. If a curve, such as the lowest curve in Fig. 5, is observed, the steady state of η_t has not been reached and the test needs to be longer to obtain an accurate steady state value of η_t. While WBT provides only an average value of thermal efficiency for the entire test (η_{avg}), η_t analysis will allow for cookstoves to be compared at various points of operation.

Finally, when comparing cookstoves at earlier points of operation it is important to be careful that noise is not a significant factor. In the early part of the test the water heating is extremely dominant and the temperature difference has not become large enough to overcome noise in the thermocouple readings. This is evident for the η_t predictions below 100 s in Fig. 5. Sudden temperature reading changes within the accuracy of the thermocouple in the first 30 s of the test can sometimes even give physically impossible values of η_t. If repeated runs are averaged over the same time the extreme variability of the early part of the test is corrected, the false negatives are no longer an issue and the curve becomes smooth.

Conclusions

η_t of a cookstove was modeled using the equations and assumptions outlined in this work. These assumptions included linear mass loss of wood, linear increase of charcoal mass, and a mass transfer coefficient that is independent of time and temperature. To verify the accuracy of the prediction, four validation experiments based on the standard WBT protocol were conducted and the calculated η_{avg} for each validation experiment were compared with η_t predictions. All of the η_t predictions had similar values compared to η_{avg} at the given time, leading to validation of the predictions.

Analysis of η_t resulted in several insights not available from the traditional η_{avg} using the WBT protocol. First, the amount of time and temperature increase required to get an accurate view of the η_{avg} of a hot start may be significantly shorter than the time required to accomplish the task outlined in the WBT protocol. It may therefore be possible to measure η_{avg} with much smaller temperature differences than are currently recommended although this may interfere with other uses of the WBT. This could decrease the time and wood requirements of biomass cookstove testing. Second, the experimental time may vary between the cold and hot start phases to obtain steady state η_t values. At least for the high thermal mass stove used in these experiments, there is a significant difference in the amount of time required for η_t to reach steady state for a cold start phase versus a hot start phase. Third, determining η_t provides validation as to if and when η_{avg} has reached steady state. Fourth, determining and comparing η_t changes between experimental runs lead to some valuable experimental findings. Investigation of the curve of the η_t showed the causes of the two lowest cold start η_{avg} measurements were 1) a physical change in the system and 2) not running the test for long enough. These findings would not have been obvious with a traditional WBT. Using predicted curves of η_t can therefore be very useful for researchers who wish to find ways to more efficiently compare cookstoves and simultaneously improve the consistency of the testing of an individual cookstove. Just a small modification of measuring temperature with time in the WBT test allows one to predict beneficial η_t information in contrast to just obtaining η_{avg}.

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