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Uncertainty analysis and design guidelines of biomass cookstove thermal efficiency studies

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ABSTRACT

Many individuals in developing areas use biomass cookstoves for cooking although there are many inherent health hazards. Judging which improved cookstove to use and distinguishing the best one for a given cooking style to mitigate these hazards is challenging. Thermal efficiency (η_{th}) is one assessment parameter of cookstoves that is often used. To compare η_{th} between cookstoves or to assess the effects of a design change on η_{th}, it is important to understand how the uncertainty in η_{th} depends on measurements, input data (equipment uncertainties, literature values, etc.), and test conditions. In this work, measurement and input data uncertainties are quantified with a propagation of uncertainty analysis for a basic brick channel cookstove used in many Peruvian households. This method can be used in any study by using reasonable uncertainty values for that study. Results showed that the four main parameters contributing to 93% of the η_{th} uncertainty were the lower heating values (LHV) of wood and char, the moisture content, and the change in temperature of the water in the pot. Reducing the uncertainty of LHV of unprocessed fuels is the most difficult. If such fuels are used, reporting the LHV value and its associated uncertainty is highly valuable.

Introduction

The hazards of using biomass cookstoves on a daily basis are well documented, including the potential of asthma, cancer, carbon monoxide poisoning, and others (Mueller et al., 2011; Chowdhury, 2012; Abeliotis and Pakula, 2013; Hawley and Volckens, 2013). In addition to the personal risk of using biomass cookstoves, there are significant environmental effects. The pollutants released are greenhouse gas emissions, and the particulate matter can increase global climate change (Bond et al., 2013). Despite these health risks and the environmental damage, those living in developing regions often have no option other than the continued use of biomass to cook and to heat their homes.

Beginning in the mid-1980s, many organizations have made efforts to mitigate the health and environmental hazards by engineering and distributing more efficient, cleaner burning biomass cookstoves (Baldwin, 1987). Improved cookstove designs have ranged from wood burning rocket stoves to cookstoves specializing in the use of farming waste. Assessment of the performance of improved cookstoves has been conducted using the Water Boiling Test (WBT) or a variant thereof (Jetter et al., 2012; Manoj et al., 2013; Bailis et al., 2014; Kshirsagar and Kalamkar, 2014). Two commonly reported values from these tests are the modified combustion efficiency (MCE), often observed above 90%, and the thermal efficiency (η_{th}) which is often shown to be below 50% (Jetter et al., 2012). This work focuses on η_{th}.

Recent efforts to improve η_{th} have involved modeling the heat transfer, in whole or in part, and then improving the cookstove design (Wohlgemuth et al., 2009; Agenbroad, 2010; Andreatta and Wohlgemuth, 2010; MacCarty and Bryden, 2015). However, physical tests are still required for model validation and for comparing η_{th} of cookstoves based on changes to cookstove designs. Usually, the average η_{th} for a number of test replicates (and sometimes standard deviation or confidence interval) is reported in the literature to compare various cookstoves or to assess design changes. To effectively compare η_{th} between cookstoves or to assess the effects of a design change on η_{th}, it is important to understand how the uncertainty in η_{th} depends on measurements, input data (manufacturing specifications, literature values, etc.), and test conditions.

The uncertainty associated with measurements, input data, and test conditions can be a result of uncertainties in the models and input parameters, variability in the equipment used in testing, and random changes in test conditions such as wind speed, ambient temperature, the method in which wood is stacked within or the method in which fuel is fed into the cookstove. Valid, unbiased comparison of cookstove performance can only be made if variations in conditions in which the tests were performed and the uncertainties in measurements and input data are reported. Unfortunately, variations can also occur both with different testers and the same tester (Zube, 2010). Fortunately,

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measurement and input data uncertainties can be quantified with a propagation of uncertainty analysis based upon the equations used to calculate η_{th}. The focus of this work is to address the uncertainty of η_{th} associated with measurements and input data. Although uncertainty of η_{th} associated with various testing conditions is not the focus of this work, it is important to reemphasize the need to report testing conditions to adequately compare η_{th} reported in the literature.

Materials and methods

Testing chamber and cookstove

As shown in Fig. 1A, a cinderblock structure (1.4 m long × 0.8 m wide × 0.7 m high) was built on a rolling metal cart. The cookstove was placed in the cinderblock housing on a 6.4-mm thick metal plate. Underneath the plate was a 10 cm deep container of sand used to imitate an in-home cookstove placed on the ground. The cinderblock housing was topped by a hood through which the exhaust flowed through a fan and a flue at an approximate flow rate of 16 L/min.

The cookstove used for this study simulated a basic channel cookstove used in many Peruvian households in the Piura region. The basic design of this cookstove is simply two small, parallel walls of bricks that are placed far enough from each other to maximize the fire while still holding the cooking pot above the fire. The brick walls used in these experiments were 2.5 bricks high and 2.5 bricks long, which resulted in a wall 14 cm tall by 56 cm long and 10 cm wide. The walls were set approximately 15 cm apart. The effects of three modifications to the channel cookstove on η_{th} were investigated. First, a grate was included by adding one additional layer of bricks (adding an additional 5.5 cm to the height) and placing the grate between the lower and middle layers of brick. The intent of this modification was to reduce heat loss to the ground and to improve the combustion efficiency by increasing airflow into the combustion zone. Second, a pot skirt made of bent metal sheets to conform to the sides of the pot was added to increase heat transfer to the pot (shown in Fig. 1C). Third, the combined effects of the grate and skirt were investigated. The basic cookstove design was tested seven times, the grate addition six times, the skirt addition nine times, and the grate/skirt addition five times.

Experimental protocol

For each test, a 15-L pot (25 cm high, and 25 cm diameter) filled with 2.5 L of water was placed on the cookstove. The temperature of the water was continuously measured using a k-type thermocouple. Douglas fir was cut into uniform sticks (2 cm × 2 cm × 25 cm) for each experiment. The wood was dried in a dehydrator for approximately 24 h before testing to maintain consistency in the moisture content. The wood moisture content was measured at the beginning of each run using a wood moisture meter (MMD4E The Seeker, General Tools, New York City, NY). For all runs, the moisture content was below the detectable limit of the meter (5%). While using a moisture meter is not the preferred method for determining moisture content in the WBT protocol, it is mentioned as an option and is an inexpensive and fast method. For this study, moisture meter measurement error was used to provide a worse-case scenario as to the contribution of this measurement error to η_{th} analysis.

Fig. 1. (A) Cookstove testing chamber with a traditional Peruvian brick channel stove resting atop a metal plate. The hood vented to a chimney augmented by a fan that can be seen directly above the apex of the hood. (B) The wood was arranged in a 'log-cabin' configuration made of sticks measuring 2 cm × 2 cm × 13 cm. There were 4 layers of sticks, with each layer containing 2 sticks. (C) Skirt surrounding pot.

The WBT was performed during each run to obtain η_{th}. The wood was arranged in a 'log-cabin' configuration at the beginning of each cold start phase as shown in Fig. 1B. For the log-cabin, the sticks were cut in half and four layers of sticks were stacked, with each layer containing two sticks. The cold start is where the cookstove begins at ambient temperature. Newspaper and splintered wood were placed in the center as starter and kindling and the fire was started. At each four minute interval following the start of the fire, an alternating pattern of three wood sticks and then two wood sticks were added to the existing fire until the water boiled. At this point, the fire was extinguished by removal from the cookstove and smothering. The amount of wood and charcoal remaining was measured using a digital scale with an accuracy of ±0.5 g. The charcoal was obtained by both removing the charcoal in the combustion chamber and by shaving off the charcoal from the remaining wood with a file. After the cold start analysis, all charcoal and wood were removed from the cookstove and the process described for the cold start was repeated with a fresh pot again filled with 2.5 L of water. The only difference was that the cookstove was now warm at the beginning of the burn. This phase is called the hot start phase. Once the water boiled in the hot start phase, the fire was extinguished and the remaining wood and charcoal were weighed. Then, additional hot start phases were continued. Only runs involving the hot start phase were analyzed in this work to reduce variability in the analysis.

Calculation of the thermal efficiency, η_{th}

As previously defined (Bailis et al. 2014), η_{th} is the ratio of the energy transferred to the water in the pot (E_{pot}) to the energy available in the fuel (E_{fuel}):

$$\eta_{th} = \frac{E_{pot}}{E_{fuel}} \tag{1}$$

Monitoring the temperature of the water in the pot, measuring the mass of water that evaporated, and determining the amount of wood consumed are some of the key aspects needed to determine η_{th} (Bailis et al., 2014; Poudyal et al., 2015).

The amount of energy transferred to the pot is calculated according to

$$E_{pot} = Cp_w * m_{water,i} * \Delta T + \Delta h_{H2O,fg} * \Delta m_{water} \tag{2}$$

where Cp_w is the specific heat of water, $m_{water,i}$ is the initial mass of water in the pot, ΔT is the final temperature of water minus the initial temperature of water in the pot, $\Delta h_{H2O,fg}$ is the heat of vaporization of saturated water at the ambient pressure (often approximated as the heat of vaporization at $P_{amb} = 1$ atm or $T = 100$ °C), and Δm_{water} is the change in mass of water in the pot. In Eq. (2), the first term accounts for the energy used to heat the water and the second term accounts for the energy used in water evaporation.

The energy in the fuel is approximated as

$$E_{fuel} = f_{cd} * LHV_{wood} \tag{3}$$

where f_{cd} is the equivalent dry weight of wood consumed and LHV_{wood} is the lower heating value of the wood consumed on a dry basis. f_{cd} is a