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A unified set of experimental data for cylindrical, natural draft, shielded, single pot, wood-fired cookstoves

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ABSTRACT

This article presents a unified dataset of 63 points compiled from three published laboratory studies for the most common type of improved household cookstove used in the developing world—a cylindrical, natural draft, shielded, wood-fired cookstove. Each data point includes 11 geometric variables, thermal conductivity of the stove body and insulation, lower heating value and moisture content of the fuel, heat release rate, and efficiency. Analysis of the dataset finds that the data are consistent between the studies and consistent with the current rules of thumb for the design of cookstoves. Specifically, it was found that pot shield gap, combustion chamber height, and insulation each have approximately the same impact on stove performance, increasing efficiency from roughly 20% to 40%. In contrast increases in pot shield height above 8 cm have limited impact on efficiency. No correlation between stove performance and volumetric or plan area heat release rate was found.

Introduction

Today more than 2.7 billion people rely on traditional biomass fuels burned in small cookstoves to meet the majority of their household energy needs (IEA, 2010). The combustion of these solid fuels results in an estimated 4.3 million premature deaths each year primarily due to indoor air pollution and approximately 25% of global black carbon emissions (WHO, 2014; Bond et al., 2013). For subsistence-level families, the cost of acquiring this fuel represents a significant fraction of household time and income. For example, a recent study of village energy in rural Mali reported that 98% of household energy needs are met with small household cookstoves and that women and children worked 250 and 40 h each year, respectively, gathering fuel (Johnson and Bryden, 2012a; Johnson and Bryden, 2012b). In spite of these health, safety, and environmental risks, recent projections indicate that biomass will continue to be the dominant fuel used for cooking and household energy needs in rural, resource-poor households through 2030 (Daioglou et al., 2012). Because of this, the design and dissemination of improved cookstoves for the rural poor has been gaining increasing global attention (Rehfuess, 2006).

Although a number of groups are working on modeling improved cookstoves, the use of detailed numerical modeling for cookstove design has been limited, and today the design of small biomass fueled cookstoves is primarily a heuristic trial and error process based on previous experience, engineering judgment, rules of thumb, and experiment (MacCarty and Bryden, 2015). To date there is no dominant design basis or established design algorithm for optimizing the performance of these devices. Nor are there validated and accepted models or modeling guidelines to support the design process although much of the necessary data, experience, and equations are available. There are two types of numerical models that have been developed for cookstoves. The most common type of numerical model is a zonal model, which typically breaks the stove system into three zones—the fuel bed zone, the flame zone, and the convective heat transfer zone. The combustion and heat transfer processes within each zone are then modeled using integral models and coupled with other zones to predict efficiency, excess air, average temperatures throughout the system, and in some cases provide an indication of the emissions. Zonal models are fast, flexible within the prescribed design space, and can provide needed information for stove analysis and design related to thermal efficiency and the expected behavior of a cookstove. Less common are detailed high-fidelity models, which use the differential equations of conservation of mass, momentum, and energy to examine complex temperature profiles, local heat transfer coefficients, formation of pollutants, and combustion properties within a cookstove.

This article presents a unified dataset of 63 points compiled from three published laboratory studies, including 11 geometric variables, thermal conductivity of the stove body and insulation materials, lower heating value and moisture content of the fuel, heat release rate, and efficiency for the most common type of improved household cookstove used in the developing world—a cylindrical, natural draft, shielded, wood-fired cookstove. This dataset can be used by cookstove researchers and designers to identify gaps in the current experimental data available and to suggest those variables that should be included

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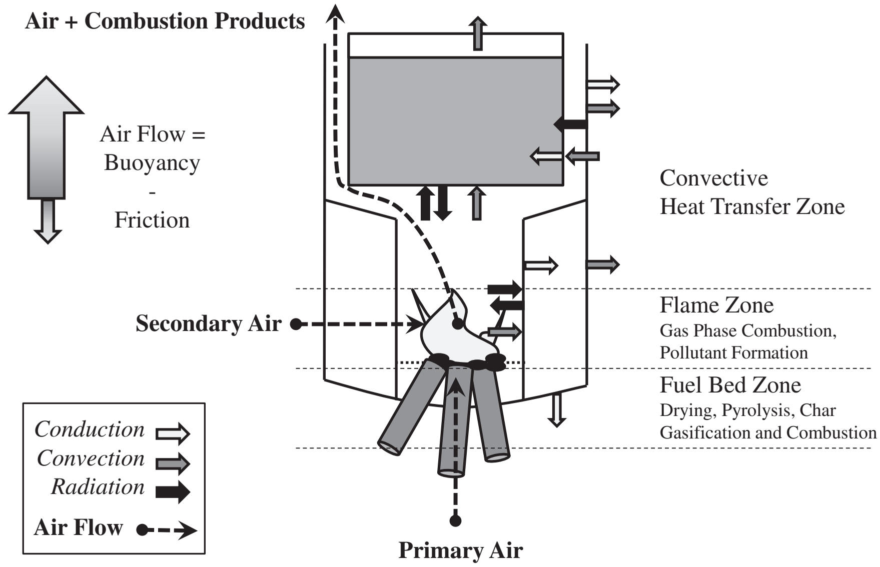

Fig. 1. A typical natural draft, shielded biomass cookstove.

when reporting the results of stove performance testing. In addition, the dataset supports development and validation of zonal models for predicting heat transfer efficiency as a function of operational and geometric variables for a natural draft, shielded, wood-burning cookstove fitted with a single, flat-bottomed shielded or unshielded pot. As gaps in the data are identified and further testing is completed, the dataset will be expanded and maintained to assist in improving and broadening models.

Background

A biomass cookstove (Fig. 1) is composed of the air handling system, the combustion chamber, the convective heat transfer region, the pot, the support structure, and the insulation. The air handling system directs the flow of primary and secondary air. The combustion chamber encloses the solid phase and gas phase combustion region and provides for radiant heat transfer from the flame and char bed to the pot. The convective heat transfer system transfers energy from the hot combustion gases to the pot, and the pot holds the food or water. The support structure and insulation provide the structural support to hold the other components together, limit energy loss from the stove, and protect the user from the heat and flame. A traditional stove such as the three-stone fire may have only one or two of these components, whereas an engineered stove may have complex designs for each of the components.

There are three primary types of biomass cookstoves based on the treatment of the combustion chamber. These are 1) an open fire in which a pot is held on top of three stones or other similar support where the airflow is uncontrolled; 2) a shielded cooking fire, often referred to as an improved stove and marketed under a number of names (e.g., rocket stoves, VITA stoves, jikos) which vary in complexity from a simple shield of metal or clay around the combustion space to more complex devices with inlets for directed control of primary and secondary air and a narrow channel around the pot to encourage combustion gases to pass closely to the pot sides; and 3) an enclosed fire with chimney, similar to stoves used for space heating but with high temperature cooking surfaces underneath which combustion gases pass from the combustion chamber and then exit to the chimney and then exhaust outside, posing less health risk due to indoor air pollution to the user.

A review of published stove studies (MacCarty et al., 2010; Jetter and Kariher, 2009; Jetter et al., 2012; Adkins et al., 2010; Bhattacharya et al., 2002a; Kar et al., 2012) reveals that the cylindrical, shielded cooking fire type is the most common improved household cookstove and is therefore the focus of this article. Due to different combustion and heat transfer behaviors, stoves which require specialized fuel such as charcoal, chips, or pellets; or stoves incorporating forced air draft (e.g., an electric fan) are not included, nor are stoves with non-cylindrical combustion chambers or round-bottomed pots.

The design variables required for development of a zonal model include a) the geometry and b) materials composing the flow path, as well as c) the operational variables of the fuel supply and firepower (i.e., the rate of heat generation). The design outcome of interest is the thermal efficiency, that is, the energy transferred into the pot as measured by water temperature rise and evaporation divided by the energy released by the fuel as measured by the lower heating value and mass of fuel burned during the test (MacCarty and Bryden,

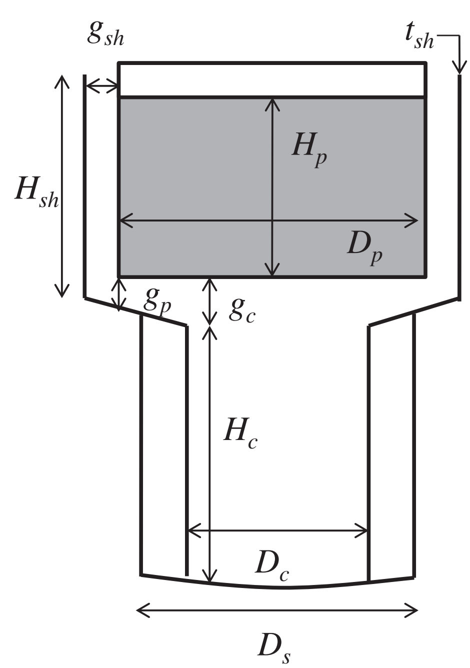

Fig. 2. Geometric variables used in the study.

2015). Based on this, the following data are needed for input into the model:

1) *Operational variables*, including firepower, fuel moisture content, and lower heating value.
2) *Geometric variables* including a description of the flow path, stove body, and pot dimensions (Fig. 2). These variables include

D_c	combustion chamber diameter
H_c	combustion chamber height
W_c	gap at the edge of the combustion chamber
W_p	gap at the edge of the pot bottom
W_{sh}	gap between the shield (if included) and pot
D_p	pot diameter
H_p	height of the water in the pot based on its occupied volume
D_{stove}	stove combustion chamber body diameter
H_{sh}	height of the shield, if included
t_{sh}	thickness of the shield material

3) *Material variables* such that the thermal conductivity of the stove body components can be determined.
4) *Thermal efficiency* as measured.

Based on a review of the literature, this article presents a compilation of these design variables and measured thermal efficiency for a natural draft, shielded, wood-burning cookstove fitted with a single, flat-bottomed shielded or unshielded pot, and it investigates the trends observed from the data.

Choice of datasets

Over the past forty years several different types of experimental studies of cookstove performance have been published. The goals of these studies have differed and therefore the data collected has varied. These studies can be broadly divided into three major categories. These are

1 *Regional field testing of stoves* to generate data related to fuel use and emissions performance for various stove–fuel combinations (Smith, 1993; Smith et al., 2000; Zhang et al., 2000; Bailis et al., 2003). The goal of this testing is to catalogue various regional stove–fuel combinations to determine the energy and pollutant data per capita for use in global inventories and policy decisions.
2 *User-based stove testing* to compare the performance of improved stoves to traditional stoves as used by stove users in their kitchens (Smith et al., 2007; Johnson et al., 2007; Roden et al., 2009). This type of study seeks to determine the fuel and emissions savings or indoor air pollution reductions offered by specific stove designs in a specific community. These studies incorporate the effects of user behavior and report results as the percent improvement in task-based metrics.
3 *Laboratory-based stove testing* to better understand cookstove performance, compare cookstove designs, and to support cookstove analysis (Jetter and Kariher, 2009; Jetter et al., 2012; MacCarty et al., 2010). The goal of these laboratory tests is to determine differences in fuel use and/or emissions performance due to stove type, model, or parametric changes to operational, material, or geometric variables. Laboratory data, though not necessarily predictive of in-field performance (Johnson et al., 2010), removes the variability of user behavior inherent in field studies.

This study focuses on identifying a consistent set of laboratory test data as a function of the stove design characteristics that can provide a unified set of experimental data for cookstove researchers and designers, enable identification of the gaps in the current experimental data available, and suggest those variables that should be included when reporting the results of stove performance testing. In addition, the dataset should be able to support the development and validation of zonal models for predicting heat transfer efficiency as a function of operational and geometric variables for a natural draft, shielded-fire wood-burning cookstove fitted with a single, flat-bottomed shielded or unshielded pot. The criteria for a laboratory-based study to be included in this dataset include the following:

1. The needed design variables and thermal efficiency are reported.
2. The stove type being tested is described. In this case, a cylindrical, natural draft, shielded, cookstove fitted with a single flat-bottomed shielded or unshielded pot and burning wood sticks as fuel.
3. The variables tested are within the design space of interest. For calculation of natural draft due to buoyancy in this case, the pot diameter must be greater than the combustion chamber diameter, and the stove must be tall enough or utilize a pot shield such that the height of the flow exit is greater than 13 cm.
4. The thermal performance characteristics are reported in terms of stove design characteristics, preferably including parametric variation.

Three articles were identified to contain data points that met criteria 2–4 and either provided nearly enough data for criteria 1 that the missing pieces could be estimated, or were recent enough to include physical stove prototypes or primary data that were currently available from the researchers. These included a parametric study of a shielded fire stove (Bussmann and Prasad, 1986), five of the stoves in a laboratory testing series (MacCarty et al., 2010), and two of the stoves tested in a second testing series (Jetter et al., 2012). Each of these stoves is shown in Fig. 3. Several other studies that may provide additional data points but are not incorporated here include (Bhattacharya et al., 2002a) which presented a parametric study of fuel moisture, firepower, and pot size for a single suitable stove but was missing details regarding some reference stove geometric and material data; and the stove was likely too short for the buoyant flow model. A concurrent emission factor study (Bhattacharya et al., 2002b) included a taller version of that stove but included no parametric variation, nor was the experimental firepower reported. The predecessor to the selected stove comparison by Jetter et al. (2012), the study by Jetter and Kariher (2009) , provided testing of two stoves that were duplicated in MacCarty et al. (2010) and did not include parameter variations and are thus not included.

In Bussmann and Prasad (1986), a shielded fire cookstove prototype with primary and secondary air constructed of sheet metal was modeled and experimentally validated through parametric variations of design variables under constant operating conditions. Geometric variations included steps of D_p, H_c, W_c, W_p, W_{sh}, H_{sh}, as well as the insulation of the combustion chamber (D_s and k_s), for a total of 34 data points. The test protocol sought to operate the stove at a constant 4 kW firepower for about 1 h with the covered pot holding an unspecified amount of water; however, concurrent publications (Prasad et al., 1985) indicated that the pots were filled 2/3 full. The water quantity was estimated as 5 l for the 20 and 24 cm diameter pots, and 7.5 l for the 28 cm pot. Thermal efficiency was reported; however, the standard deviation, confidence interval, and the number of replicate tests were not reported and were not available. As a consequence, the results need to be used with care (Wang et al., 2014). In some of the parametric variations, the default values of several constant variables were not specified explicitly but were inferred by comparison to results and variables in other variations. The parameters for which a value is estimated, are indicated by the gray shaded cells in Table 1. There is no indication of the moisture content or heating value of the fuel, so these are assumed to be 0% for dry fuel with a LHV of 18.6 MJ/kg$_{as\text{-}recd}$ (Ragland and Baker, 1991), and it was assumed that the reported constant 4 kW firepower accounts for these. The thermal conductivity of the sheet metal, assumed to be 0.5 mm thick, and the added fiberglass insulation were not specified but were determined from the literature per Table 2.

The stove testing report of MacCarty et al. (2010) presented laboratory test results of fifty cookstoves, including those with chimney, electric fan, and prepared or liquid fuels in addition to the single-pot shielded fire of interest here. Of these, several did not meet the criteria of the model due to a combustion chamber that was a) too short, b) of diameter larger than that of the pot, or c) not cylindrical. However, five stoves were suitable, including two that were tested both with and without a pot shield. These stoves included the StoveTec™ fireclay brick one- and two-door stoves with and without pot shield, the Mauritania stove with a heavy concrete-like combustion chamber, the World Food Program (WFP) stove with a wood ash filled combustion chamber, and the UCODEA stove with a pumice brick combustion chamber. These provided a total of 17 data points which used the Water Boiling Test (WBT) (Bailis et al., 2007) to bring 5 l of water with no lid from room temperature to boiling at high power, or to maintain the water at a simmer at low firepower. The firepower was not prescribed or controlled, but the average firepower was determined by the feed rate of fuel required to bring the water to boil as quickly as possible without being excessively wasteful of fuel, or to maintain the water 3 °C below boiling during simmer, as indicated by the test protocol. Specific consumption was reported in lieu of thermal efficiency; however, thermal efficiency measurements were available from the primary data incorporating the average of 3 to 9 WBT results for cold start, hot start and simmer. Stove geometry details were not provided, but the physical stove models were available for measurement. Thermal conductivity of the materials was not reported but determined per Table 2, and the thickness of the sheet metal pot shields was assumed to be 0.5 mm.

Jetter et al. (2012) reported the laboratory fuel and emissions performance of 23 stoves, also including stove designs and fuels not applicable to this dataset. Two stoves met the criteria, including the StoveTec™ fireclay brick one-door (also tested in MacCarty et al., 2010) and the Envirofit™ perlite-filled stove. These were evaluated at medium and high firepower and two levels of fuel moisture content for a total of 12 data points. The WBT was used to bring 5 l of water with no lid from

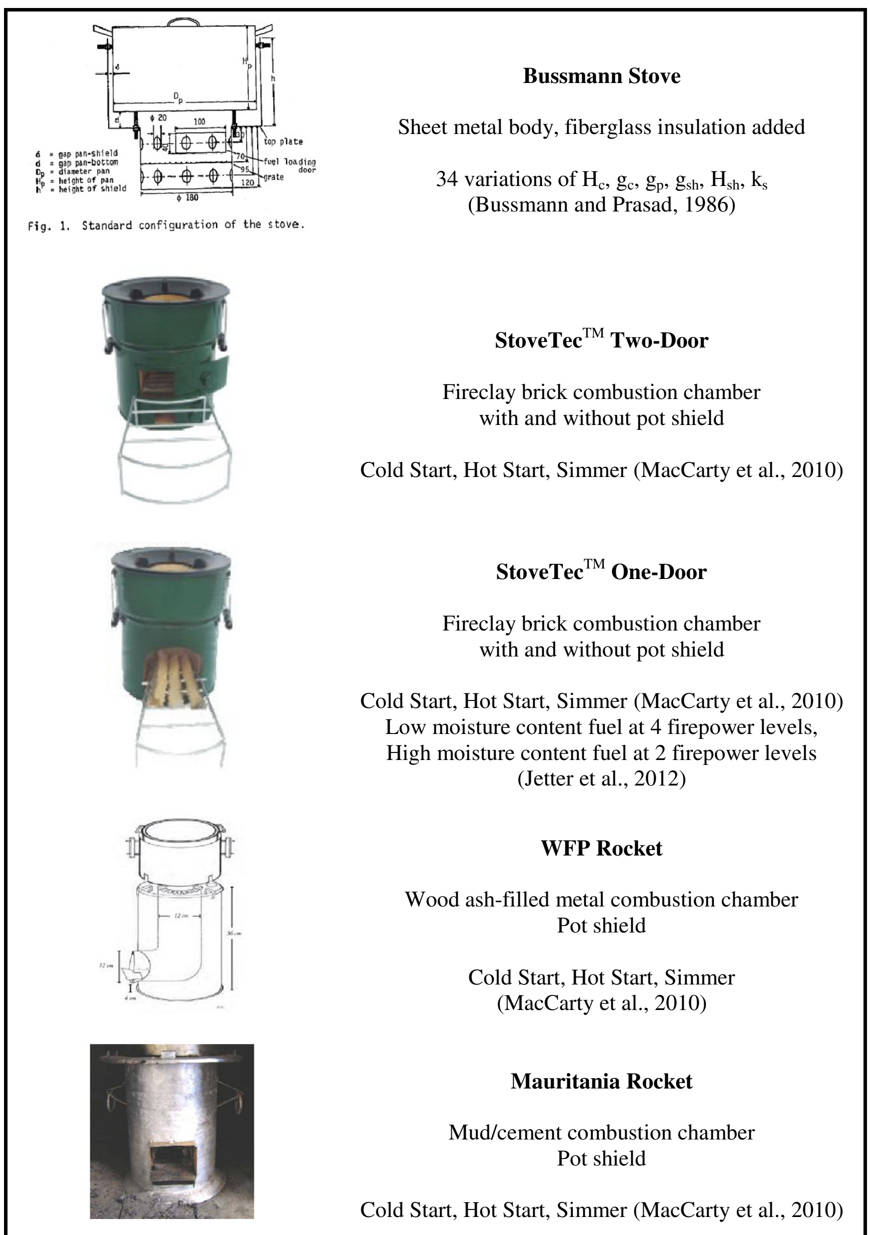

Fig. 3. Stoves and variations used in the studies.

UCODEA Rocket

Pumice combustion chamber
Integral pot shield

Cold Start, Hot Start, Simmer (MacCarty et al., 2010)

Envirofit™ G3300

Perlite-filled metal combustion chamber
Pot shield

Low moisture content fuel at 4 firepower levels,
high moisture content fuel at 2 firepower levels
(Jetter et al., 2012)

Fig. 3 (*continued*).

room temperature to boiling at medium or high power, where firepower was not prescribed or held constant but calculated from fuel consumption. The average and standard deviation of thermal efficiency from three WBTs was reported, with the exception of low power tests. Stove geometry details were not provided, but the physical stove models were available for measurement. Thermal conductivity of the materials was not reported but determined per Table 2, and the thickness of the sheet metal pot shields was assumed to be 0.5 mm.

From the three selected studies, 63 reported experimental data points were available. As a whole, the group includes variation of each geometric, material, and operating design variable. Fig. 3 shows the cookstove models and Table 1 provides a collection of the measured thermal efficiency and 15 design variables for the 63 data points. In addition, Table 1 provides the number of replicate tests and the confidence interval for each of the data points for the Jetter et al. (2012) and the MacCarty et al. (2010) studies. As noted earlier, the standard deviation, confidence interval, and the number of replicate tests were not reported (and were not available from other sources) for the Bussman and Prasad (1986) study. As a consequence, the results of the Bussman and Prasad (1986) study need to be used with care (Wang et al., 2014). Table 2 provides the thermal conductivity of the materials used. Table 3 shows the range and averages of each variable, indicating the design space covered by the dataset.

Analysis of the dataset

Investigation of the dataset as a whole can help indicate the consistency between the three studies and reliability of the results, the trends in performance relative to the design variables, and the gaps in the data. In this section we specifically examine four rules of thumb currently used in the design of small household cookstoves. One limitation of this study is the use of single variable analysis rather than multivariate analysis in which the interconnection between variables is considered. More detailed analysis of this data may reveal additional interconnections between the various stove parameters and stove performance. And we are continuing to develop a detailed correlation between the design parameters and the stove performance that can be used in conceptual design. The goal here is to examine the current rules of thumb used in the design of household cookstoves, judge how well these rules are supported by the available data, suggest an accepted set of variables for stoves testing, and suggest further experimental studies to fill in the gaps. Incorporating results from all studies in this way increases the value of the findings from each individual study, and confirms the current qualitative knowledge and the use of the current rules of thumb in the development and design of small household cookstoves. As discussed in Bryden et al. (2005) these rules of thumb include

1. *Using a pot shield increases the thermal efficiency of a cookstove, and minimizing the gaps between the pot and pot shield while maintaining the airflow further increases the thermal efficiency of the stove.*
   Fig. 4 examines the thermal efficiency of the cookstove as a function of the ratio between the pot shield gap and the radius of the pot. As shown, the data from the three studies are consistent. As expected, with the exception of two data points, the use of the pot shield improves cookstove thermal efficiency. As the gap between the pot shield and the pot increases, the thermal efficiency of the stove tends towards that of the stoves with no pot shield. The thermal efficiency of the stoves with the smallest gaps is roughly double the efficiency of a stove with no pot shield. Fig. 5 examines thermal efficiency as a function of the pot shield gap and highlights three different pot diameters: 20 cm, 24 cm, and 28 cm. As in Fig. 4, with the exception of two data points the use of a pot shield improves cookstove thermal efficiency. As the pot shield gap increases, the thermal efficiency of the stove tends towards that of a stove with no pot shield, and the smallest pot shield gap roughly doubles the efficiency of a stove. In addition, increasing the diameter of the pot consistently increases the efficiency of the cookstove. There is some indication in Fig. 5 data that for smaller diameter pots as the gap becomes smaller (in the cases shown, 8 mm), the thermal efficiency of the stove is reduced. This would be expected as smaller gaps can choke the airflow through the stove. However, there is no indication of this effect in Fig. 4 and there is limited data. This suggests that more experimental data examining this affect are needed. In addition, as shown in Figs. 4 and 5, the majority of the experimental results are gathered in only a few bands and that more data are needed to more fully describe impact of a pot shield gap on thermal efficiency across the potential design range. The variability in the results occurs due to differences in stove design.
2. *Although the use of a pot shield increases the thermal efficiency of a cookstove, this impact diminishes as the height of the pot shield increases.*
   Examining the entire dataset does not provide quantitative or qualitative evidence of impact of the height of the pot shield on the thermal efficiency of the stove. As shown in Fig. 6, the parametric shield height study from Bussmann and Prasad (1986) included in data set 1 suggests that thermal efficiency of a stove does increase by about 10% up to a height of approximately 8 cm. The other studies examine the pot shield heights of 7.6 cm and greater. This lack of data and the confounding effects of other variables obscure trends

in shield height within the dataset as a whole, and it is not possible to examine the combined impact of pot shield gap, pot diameter, and pot shield height. As pot shields may be a consumer adoption issue, developing a better understanding of these issues would be helpful in stove design.

3. *A shorter combustion chamber increases stove thermal efficiency.*
A shorter combustion chamber places the pot in closer proximity to the fuel bed. It is generally thought that this closer proximity of the pot results in a greater proportion of the radiation heat transfer from the bed of char and the flame into the pot bottom. In addition, the exposed area of the combustion chamber wall is smaller resulting in fewer heat losses to the wall and higher gas temperatures, increasing the convective heat transfer into the pot. Offsetting this view is the concern that shorter combustion chambers reduce the time available to combust the pyrolysis gases and may result in lower combustion efficiencies resulting in reduced stove thermal efficiency.

Table 1
Variables within the data set.[1,2]

Stove	η	CI η	N	D_c	H_c	W_c	W_p	W_{sh}	V_w	D_p	H_p	H_{sh}	D_{stove}	k_{stove}	t_{sh}	k_{sh}	LHV	MC	q	CI q
	%	90%		cm	cm	cm	cm	cm	L	cm	cm	cm	cm	W/m·K	cm	W/m·K	MJ/kg	%	kW	90%
Vary W_{sh}, Dp[3]	0.35	–	–	18.0	10.0	3.5	3.5	0.4	5	20.0	15.9	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.37	–	–	18.0	10.0	3.5	3.5	0.7	5	20.0	15.9	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.33	–	–	18.0	10.0	3.5	3.5	1.0	5	20.0	15.9	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.30	–	–	18.0	10.0	3.5	3.5	1.3	5	20.0	15.9	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.27	–	–	18.0	10.0	3.5	3.5	1.6	5	20.0	15.9	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.39	–	–	18.0	10.0	3.5	3.5	0.4	5	24.0	11.1	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.40	–	–	18.0	10.0	3.5	3.5	0.7	5	24.0	11.1	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.37	–	–	18.0	10.0	3.5	3.5	1.0	5	24.0	11.1	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.33	–	–	18.0	10.0	3.5	3.5	1.3	5	24.0	11.1	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.30	–	–	18.0	10.0	3.5	3.5	1.6	5	24.0	11.1	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.47	–	–	18.0	10.0	3.5	3.5	0.4	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.42	–	–	18.0	10.0	3.5	3.5	0.7	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.39	–	–	18.0	10.0	3.5	3.5	1.0	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.36	–	–	18.0	10.0	3.5	3.5	1.3	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.33	–	–	18.0	10.0	3.5	3.5	1.6	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
Vary W_c[3]	0.36	–	–	18.0	13.0	0.5	0.5	1.0	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.38	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.37	–	–	18.0	12.0	1.5	1.5	1.0	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.35	–	–	18.0	11.0	2.5	2.5	1.0	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.32	–	–	18.0	10.0	3.5	3.5	1.0	7.5	28.0	12.2	17.8	18.10	26.2	0.05	26.2	18.60	0	4.0	–
Vary H_{sh}[3]	0.33	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	1.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.36	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	2.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.39	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	4.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.41	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	8.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.42	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	12.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.42	–	–	18.0	12.5	1.0	1.0	1.0	7.5	28.0	12.2	16.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
Vary H_c, No insulation[3]	0.40	–	–	18.0	10.0	1.0	1.0	1.0	7.5	28.0	12.2	1.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.37	–	–	18.0	17.5	1.0	1.0	1.0	7.5	28.0	12.2	1.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.35	–	–	18.0	22.5	1.0	1.0	1.0	7.5	28.0	12.2	1.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
	0.30	–	–	18.0	26.0	1.0	1.0	1.0	7.5	28.0	12.2	1.0	18.10	26.2	0.05	26.2	18.60	0	4.0	–
Vary H_c, Insulation[3]	0.42	–	–	18.0	10.0	1.0	1.0	1.0	7.5	28.0	12.2	1.0	20.10	0.038	0.05	26.2	18.60	0	4.0	–
	0.41	–	–	18.0	17.5	1.0	1.0	1.0	7.5	28.0	12.2	1.0	20.10	0.038	0.05	26.2	18.60	0	4.0	–
	0.39	–	–	18.0	22.5	1.0	1.0	1.0	7.5	28.0	12.2	1.0	20.10	0.038	0.05	26.2	18.60	0	4.0	–
	0.38	–	–	18.0	26.0	1.0	1.0	1.0	7.5	28.0	12.2	1.0	20.10	0.038	0.05	26.2	18.60	0	4.0	–

(continued on next page)

Table 1 *(continued)*

Stove	η	CI η	N	D_c	H_c	W_c	W_p	W_{sh}	V_w	D_p	H_p	H_{sh}	D_{stove}	k_{stove}	t_{sh}	k_{sh}	LHV	MC	q	CI q
	%	90%		cm	cm	cm	cm	cm	L	cm	cm	cm	cm	W/m·K	cm	W/m·K	MJ/kg	%	kW	90%
Stovetec 2D[4]	0.27	0.03	3	10.0	20.0	2.5	1.0	0.8	5	24.0	11.1		26.0	1.0			19.26	12	4.1	0.4
	0.36	0.09	3	10.0	20.0	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	19.26	12	3.9	0.7
	0.20	0.02	3	10.0	20.0	2.5	1.0	0.8	5	24.0	11.1		26.0	1.0			19.26	12	2.2	0.5
	0.30	0.03	3	10.0	20.0	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	19.26	12	2.0	0.5
Stovetec 1D[4]	0.24	0.02	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1		26.0	1.0			19.26	14	3.8	0.4
	0.33	0.02	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	19.26	14	4.0	0.3
	0.20	0.01	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1		26.0	1.0			19.26	14	2.2	0.3
	0.30	0.08	2	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	19.26	14	2.0	0.9
WFP[4]	0.37	0.18	4	12.0	28.0	3.0	1.5	1.0	5	24.0	11.1	12.3	32.0	0.18	0.05	26.2	19.26	11	5.5	1.2
	0.33	0.11	4	12.0	28.0	3.0	1.5	1.0	5	24.0	11.1	12.3	32.0	0.18	0.05	26.2	19.26	11	6.3	0.9
	0.26	0.07	3	12.0	28.0	3.0	1.5	1.0	5	24.0	11.1	12.3	32.0	0.18	0.05	26.2	19.26	11	2.2	0.5
Mauritania[4]	0.18	0.01	3	12.0	36.0	3.0	3.0	1.6	5	24.0	11.1	14.1	28.0	1.7	0.05	26.2	19.26	5	4.1	0.4
	0.20	0.01	3	12.0	36.0	3.0	3.0	1.6	5	24.0	11.1	14.1	28.0	1.7	0.05	26.2	19.26	5	4.6	0.3
	0.18	0.00	1	12.0	36.0	3.0	3.0	1.6	5	24.0	11.1	14.1	28.0	1.7	0.05	26.2	19.26	5	3.3	0.0
UCODEA[4]	0.30	0.12	2	12.4	29.0	2.7	1.2	1.2	5	31.0	6.6	7.6	23.0	0.6	0.05	26.2	19.26	7	5.8	1.1
	0.31	0.06	2	12.4	29.0	2.7	1.2	1.2	5	31.0	6.6	7.6	23.0	0.6	0.05	26.2	19.26	7	5.6	0.3
	0.27	0.02	2	12.4	29.0	2.7	1.2	1.2	5	31.0	6.6	7.6	23.0	0.6	0.05	26.2	19.26	7	3.7	2.1
Stovetec 1D[5]	0.35	0.06	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	17.74	9	3.9	0.7
	0.33	0.06	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	17.74	10	5.1	1.0
	0.35	0.04	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	17.74	21	2.8	0.1
	0.36	0.02	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	17.74	20	3.6	0.5
	0.37	0.01	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	17.74	9	2.8	0.3
	0.35	0.03	3	10.0	23.3	2.5	1.0	0.8	5	24.0	11.1	8.0	26.0	1.0	0.05	26.2	17.74	9	3.8	0.6
Envirofit[5]	0.38	0.02	3	9.5	19.6	3.2	1.2	1.0	5	24.0	11.1	8.0	25.0	0.05	0.05	26.2	17.74	9	4.4	0.8
	0.41	0.04	3	9.5	19.6	3.2	1.2	1.0	5	24.0	11.1	8.0	25.0	0.05	0.05	26.2	17.74	9	4.9	0.9
	0.37	0.04	3	9.5	19.6	3.2	1.2	1.0	5	24.0	11.1	8.0	25.0	0.05	0.05	26.2	17.74	22	2.7	0.2
	0.41	0.05	3	9.5	19.6	3.2	1.2	1.0	5	24.0	11.1	8.0	25.0	0.05	0.05	26.2	17.74	22	3.3	0.1
	0.36	0.00	3	9.5	19.6	3.2	1.2	1.0	5	24.0	11.1	8.0	25.0	0.05	0.05	26.2	17.74	9	2.9	0.5
	0.40	0.06	3	9.5	19.6	3.2	1.2	1.0	5	24.0	11.1	8.0	25.0	0.05	0.05	26.2	17.74	10	3.8	0.5
Minimum	0.18	0.00	1.00	9.5	10.0	0.5	0.5	0.4	5.0	20.0	6.6	1.0	18.10	0.04	0.05	26.2	17.74	0	2.0	0.0
Maximum	0.47	0.18	4.00	18.0	36.0	3.5	3.5	1.6	7.5	31.0	15.9	17.8	32.00	26.20	0.05	26.2	19.26	22	6.3	2.1
Average	0.34	0.04	2.86	14.6	18.2	2.5	1.8	1.0	6.0	25.5	11.7	10.8	22.01	12.82	0.05	26.2	18.61	5	3.9	0.6

Notes

[1]Grey cells indicate parameters for which a value is estimated as discussed in the text.

[2]η — efficiency; CI — 90% confidence interval; N — number of replicate tests; D_c — combustion chamber diameter; H_c — combustion chamber height; W_c — gap at the edge of the combustion chamber; W_p — gap at the edge of the pot bottom; W_{sh} — gap between the shield (if included) and pot; V_w — volume of water; D_p — pot diameter; H_p — height of the water in the pot based on its occupied volume; H_{sh} — height of the shield, if included; D_{stove} — stove combustion chamber body diameter; k_{stove} — stove body material conductivity; t_{sh} — thickness of the shield material; k_{sh} — shield material conductivity; LHV — lower heating value on a dry basis; MC — as-received moisture content; q — fire power (i.e., heat release rate).

[3]Bussmann and Prasad (1986).

[4]MacCarty et al. (2010).

[5]Jetter et al. (2012).

Fig. 7 shows the thermal efficiency of a stove as a function of combustion chamber height. As shown, the poorest performing stove has a thermal efficiency of 18% and the tallest combustion chamber height of 36 cm. In contrast the best performing stove in the data set has a thermal efficiency of 47% and the shortest combustion chamber height of 10 cm. Beyond this observation, there is a general trend of improving stove performance with shorter combustion chambers; however, this is confounded by multiple variables in the various stove designs. The parametric study of Bussmann and Prasad (1986), highlighted in Fig. 7, does provide good evidence and shows that the impact of the combustion height on thermal efficiency is less pronounced when the combustion chamber is insulated. As the combustion chamber height, temperature, and transit time are tightly tied to combustion efficiency and the formation of the undesirable products of incomplete combustion, more data and analysis are needed to more fully understand combustion chamber sizing.

Table 2
Thermal conductivity.

Material	Thermal conductivity W/m·K
Sheet metal[a]	26.2
Concrete[a]	1.7
Fireclay brick[b]	1.0
Pumice brick[b]	0.6
Wood ash[a]	0.18
Perlite[b]	0.05
Fiberglass[b]	0.04

[a] Avalonne and Baumeister (2007).
[b] Incropera et al. (2007).

Table 3
Range of variables in data set.

			Minimum	Maximum	Average
Geometrical variables					
Combustion chamber diameter	D_c	cm	9.5	18.0	14.6
Combustion chamber height	H_c	cm	10.0	36.0	18.2
Gap at combustion chamber	W_c	cm	0.5	3.5	2.5
Gap at pot corner	W_p	cm	0.5	3.5	1.8
Shield gap[a]	W_{sh}	cm	0.4	1.6	1.0
Stove diameter	D_{stove}	cm	18.10	32.0	22.0
Shield height[a]	H_{sh}	cm	1.0	17.8	10.8
Shield thickness[a]	t_{sh}	cm	0.05	0.05	0.05
Pot diameter	D_p	cm	20.0	31.0	25.5
Pot water height	H_p	cm	6.6	15.9	11.7
Water volume	V_w	L	5.0	7.5	6.0
Operational variables					
Lower heating value, dry basis	LHV	MJ/kg	17.74	19.26	18.61
Moisture content, as-received	MC	%	0	22	5
Firepower	q	kW	2.0	6.3	3.9

[a] Range and average are only for tests that included a pot shield.

4. *A stove with an insulated combustion chamber is more efficient.* Rules of thumb, previous models (Baldwin, 1987), and common sense indicate that an insulated combustion chamber will improve the thermal efficiency of a stove by reducing heat losses to the surroundings. Fig. 8 examines the thermal efficiency of a stove as a function of the thermal conductance of the stove body. Thermal conductance is the inverse of thermal resistance (i.e., as the amount of insulation increases, the thermal conductance decreases). As shown in Fig. 8, the least efficient stove in the dataset has the greatest thermal conductance. In addition a strong trend in which lower conductance results in higher efficiency can be seen. The same trend is seen in the paired data points from Bussman and Prasad's (1986) parametric data in Fig. 7. As expected, as the combustion chamber decreases in height, the area available for losses to the environment decreases and insulation has a smaller impact on overall thermal efficiency.

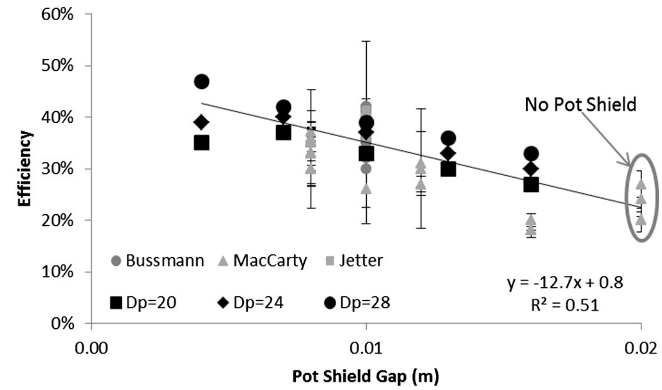

Fig. 5. Thermal efficiency of a stove as a function of the pot shield gap. Pot diameters of 20, 24, and 28 cm are highlighted. 90% confidence intervals are shown for the Jetter and MacCarty data.

As seen from the discussion above, the unified dataset developed from the literature is internally consistent and supports the general stove design guidelines that stoves with well insulated combustion chambers, pot shields with smaller gaps, and shorter combustion chambers have higher thermal efficiency. In addition, it is interesting to note that results between the various testing laboratories are generally consistent with no significant outliers or surprises. Although this may seem like an obvious conclusion, there can be differences in fire tending skills and in the instrumentation used as well as in other details.

It has been suggested by some that *greater fire intensity results in greater thermal efficiency*. Although it might be anticipated that higher heat release rates would show the same impact as decreasing the height of the combustion chamber (i.e., more energy release and less area for energy loss), it is also challenging to convect and radiate the energy released into the pot bottom and sides before the hot combustion gases exit the stove. Beyond this, higher heat release rates may increase turbulence and combustion chamber temperatures, but there are other factors that have a stronger impact on both turbulence and combustion temperatures. There are two aspects of fire intensity that can be examined using the unified dataset: the volumetric heat release rate (Fig. 9) and the heat release rate per unit combustion chamber plan area (Fig. 10). As shown, in both cases there appears to be no clear correlation between heat release rates and the thermal efficiency. This supports the judgment of Bussman and Prasad who held the firepower and combustion chamber plan area constant during their parametric tests reported in (Bussmann and Prasad, 1986).

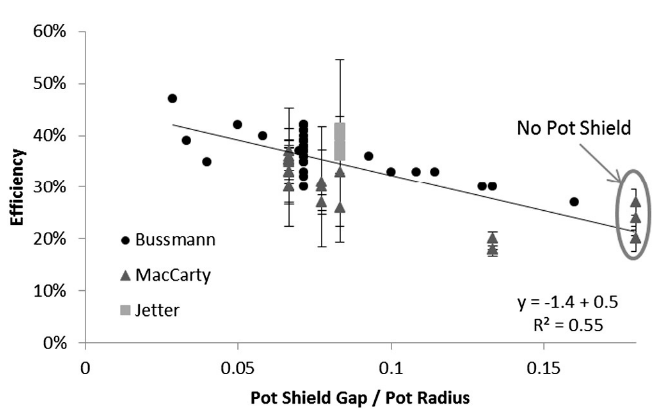

Fig. 4. Thermal efficiency of a stove as a function of the ratio of the pot shield gap to the pot radius. 90% confidence intervals are shown for the Jetter and MacCarty data.

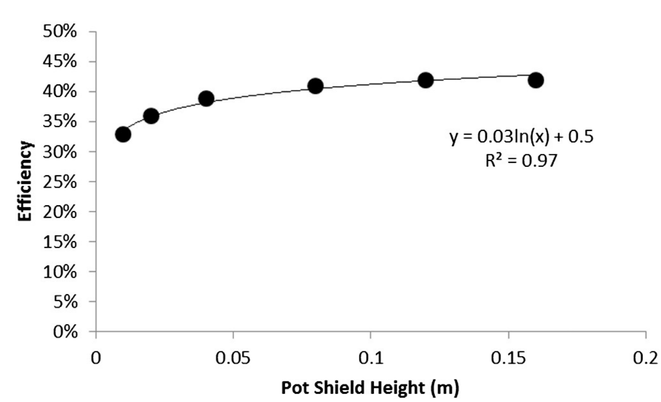

Fig. 6. Thermal efficiency of a stove as a function of pot shield height based on data from Bussman and Prasad's parametric study (1986).

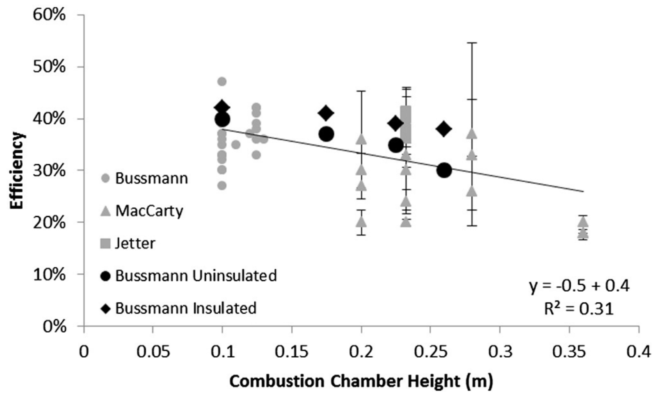

Fig. 7. Thermal efficiency of a stove as a function of combustion chamber height. The data points from the parametric study of Bussman and Prasad (1986) for insulated and uninsulated cookstoves are highlighted. 90% confidence intervals are shown for the Jetter and MacCarty data.

Conclusions and future work

The experimental literature for laboratory testing of cylindrical, natural draft, shielded, single pot, wood-burning household cookstoves was reviewed and a unified dataset of the experimental results available is presented. The dataset includes 63 data points and includes 11 geometric variables, thermal conductivity of the stove body and insulation materials, lower heating value and moisture content of the fuel, heat release rate, and efficiency. This provides an initial consistent data set to support the understanding and preliminary design of natural draft, shielded, single pot, wood-burning cookstoves. A review of the dataset shows that it is internally consistent as evidenced by banded data with no outliers and follows known trends and qualitatively supports the current rules of thumb used in stove design. Specifically, it was found that pot shield gap, combustion chamber height, and insulation each have approximately the same impact on stove performance, increasing efficiency from roughly 20% to 40%. In contrast after about 5 cm, increases in pot shield height have limited impact on efficiency. No correlation between stove performance and volumetric or plan area heat release rate was found. One limitation of this study is the use of single variable analysis, and a further study is needed to develop a detailed correlation between the design parameters and the stove performance.

In addition, this dataset provides a starting place for the development of additional stoves testing and provides a clear set of variables that are needed when reporting the results of stove performance testing. Future experimental work should involve expansion and broadening of the dataset and stove types covered. Although several variations of each design variable were included in this study, additional data points for unshielded pots, variation of fuel moisture content, and an overall expansion of the design space for this stove type are needed. Also there are gaps in the dataset particularly in the areas of pot shield gap and pot shield height. Similar datasets are needed for round bottomed pots, and for stoves that utilize charcoal, prepared fuels, and/or a forced draft.

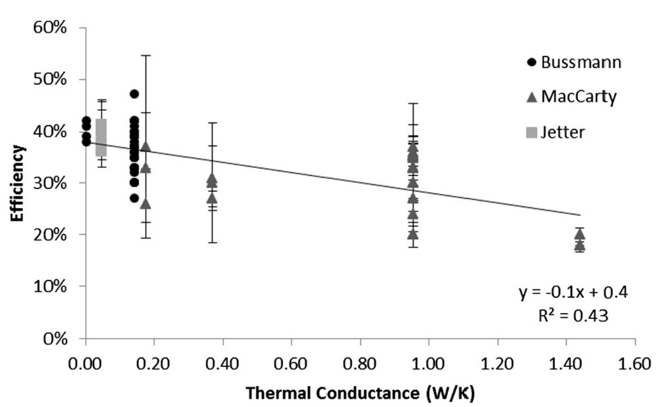

Fig. 8. Thermal efficiency as a function of stove body conductance. 90% confidence intervals are shown for the Jetter and MacCarty data.

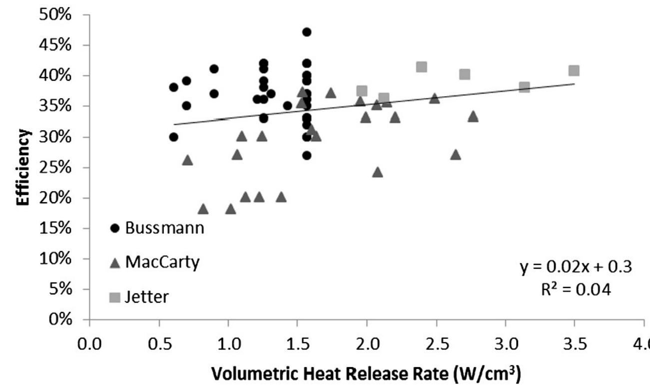

Fig. 9. Thermal efficiency as a function of the volumetric heat release rate.

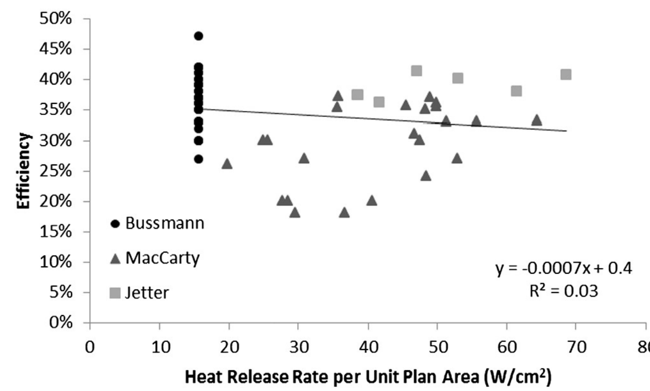

Fig. 10. Thermal efficiency as a function of the heat release rate per unit combustion chamber plan area.

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