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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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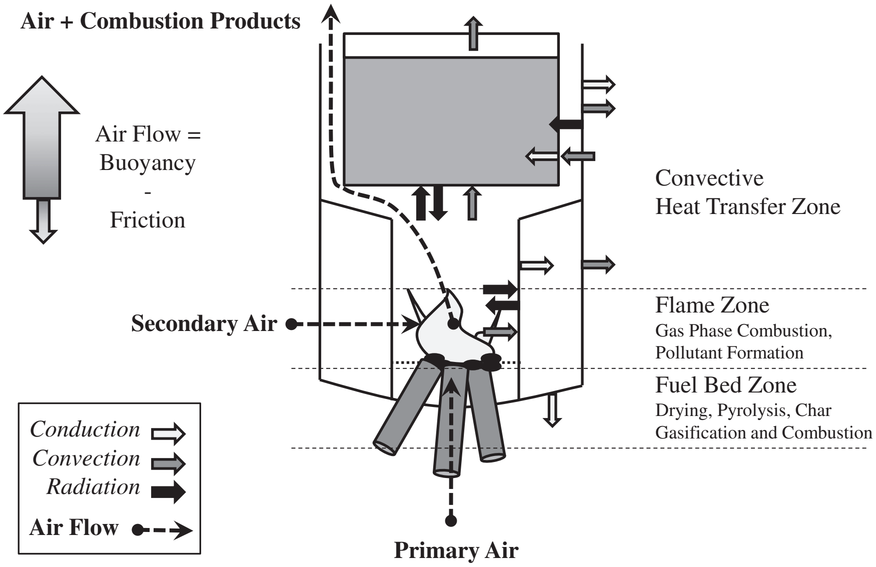

Fig. 1. A typical natural draft, shielded biomass cookstove.

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,

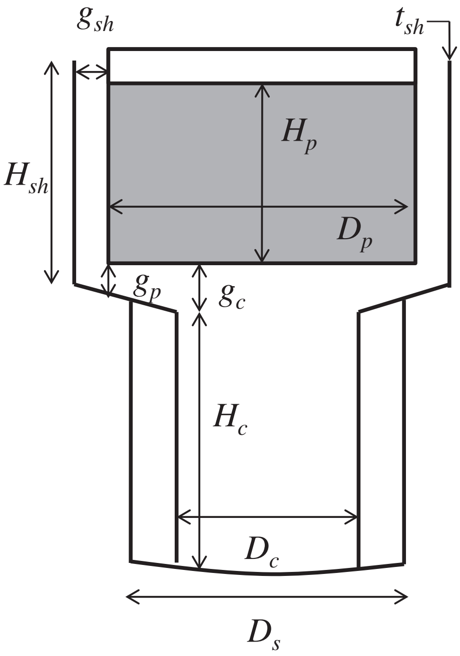

Fig. 2. Geometric variables used in the study.