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# Modeling of household biomass cookstoves: A review

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ABSTRACT

This article reviews the cookstove modeling literature for one- to three-burner natural draft, wood-fired cookstoves fueled with solid unprocessed biomass ranging in size from 1 to 20 cm and operated by an individual in a residential setting. These household cookstove models are organized around the three major zones of the cookstove system: the fuel bed, the gas phase reaction zone, and the heat transfer zone. Today's household biomass cookstove models are coupled steady-state models with simplified algebraic relationships for the packed bed; computational fluid dynamics with a four-equation set global reaction scheme for $CO_2$, CO, $H_2$, $H_2O$, and hydrocarbons in the gas phase reaction zone; and generic correlations or computational fluid dynamics models in the heat transfer zone. The current models do not address the production of particulate or other harmful emissions or the effects of fuel tending, varying fuel, or transient operations.

## Introduction

This paper reviews the current state of numerical modeling of the small biomass cookstoves used to meet the household energy needs of more than 2.4 billion people. Specifically, this article focuses on one- to three-burner biomass cookstoves fueled with solid unprocessed biomass ranging in size from 1 to 20 cm and operated by an individual in a residential setting. Although called cookstoves, depending on local custom and need, the primary uses of these stoves include heating water for washing, cooking meals, steeping tea, making medicines, and other household tasks (Johnson and Bryden, 2012). These types of stoves account for the majority of cookstove designs in use in the developing world today (Jetter et al., 2012; MacCarty et al., 2010). Although in some cases the issues are similar, this article does not address charcoal or coal stoves, forced draft stoves, gasifier stoves, pulverized fuel stoves, institutional scale stoves, or stoves used for space heating. Nor does this article address the issues associated with fuel processing and fuel pellets.

More than 2.4 billion people use solid biomass fuels for household cooking and heating in open fires and simple stoves (International Energy Agency (IEA), 2010). The users of these cookstoves live almost entirely in the developing world, and the individual, community, and global impacts of these household biomass cookstoves are significant. It has been estimated that indoor air pollution from solid fuel use is responsible for nearly 4 million deaths annually and accounts for approximately 4% of the burden of disease in developing countries (Lim et al., 2012; World Health Organization (WHO), 2002). The fine particulate matter, carbon monoxide, polycyclic aromatic hydrocarbons, and other emissions due to incomplete combustion within typical kitchens contribute to acute lower respiratory infections, pneumonia, and chronic obstructive lung disease; as well as adverse pregnancy outcomes and cataracts (World Health Organization (WHO), 2002; Legros et al., 2009; Bruce et al., 2006; Rehfuess, 2006). In addition, the use of biomass fuel for cooking and heating is a significant source of global black carbon emissions, which is one source of climate change (Bond et al., 2013).

Recognizing these individual, community, and global impacts, a number of groups have focused on the research and development of improved household biomass cookstoves. However, few of these efforts have focused on developing the numerical models needed for the design of cookstoves. In the past 30 years more than 500 journal articles have examined various aspects of biomass cookstoves; however, fewer than 30 of these journal articles have addressed numerical modeling of the heat transfer and combustion processes in traditional household biomass cookstoves. Because of this, today the design of these cookstoves is primarily based on experience and rules of thumb.

## Background

A traditional biomass cookstove consists of the air intake and transport system, a bed of fuel, a gas phase combustion zone, and a cookpot. There are three primary types of traditional household biomass cookstoves based on the treatment of the combustion chamber. These are

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1. Open cooking fires—these are traditional cooking fires in which a cookpot is held atop three stones or other similar support (Fig. 1a). The airflow is uncontrolled and the air is entrained in the system due to buoyancy. Generally a fire grate is not included.
2. Shielded-fire cookstove—these stoves are often referred to as improved stoves and marketed under a number of names. These devices range from a simple shield of metal or clay around the combustion space to more complex devices with inlets for the directed control of primary and secondary air (Fig. 1b). Some include electrically powered fans to control the air. In some cases a narrow channel is created around the cookpot to improve heat transfer from the combustion gases to the cookpot. There may or may not be a fire grate provided.
3. Enclosed-fire cookstoves with chimneys—these stoves are similar to stoves used for space heating but have high temperature cooking surfaces (Fig. 1c). The fire is fully enclosed within the combustion chamber. The fuel entrance may be open and permit airflow into the system. Alternately, there may be a tightly sealed fuel door and separate controls for airflow into the stove. Gases leave the combustion chamber and travel along channels underneath exposed cookpot bottoms or a large sealed plate or griddle on which pots are heated or food is directly cooked. The combustion gases then exit to the chimney and are exhausted outside of the kitchen.

The basic operation of all three types of stoves is similar. They are fueled with wood or biomaterials (e.g., dung cake or crop residues). It should be noted that there are very few models of cookstoves fired with biomaterials other than wood, and all the models included in this review are based on wood-fired cookstoves. The wood fuels that have been modeled range in size from small twigs to large unsplit branches. The as-received fuel moisture varies in moisture content from 5% to greater than 50% depending on the season, storage availability, harvest method, and curing time (Ragland and Bryden, 2011). Due to limited control of primary and secondary airflow, there is often high excess air resulting in low combustion gas temperatures, short transit times, and incomplete combustion. The challenge for designers of these devices is to create a user-friendly cooking appliance that can utilize a wide array of fuel types, sizes, and moisture contents while maintaining high heat, good turndown, high overall efficiency and low emissions.

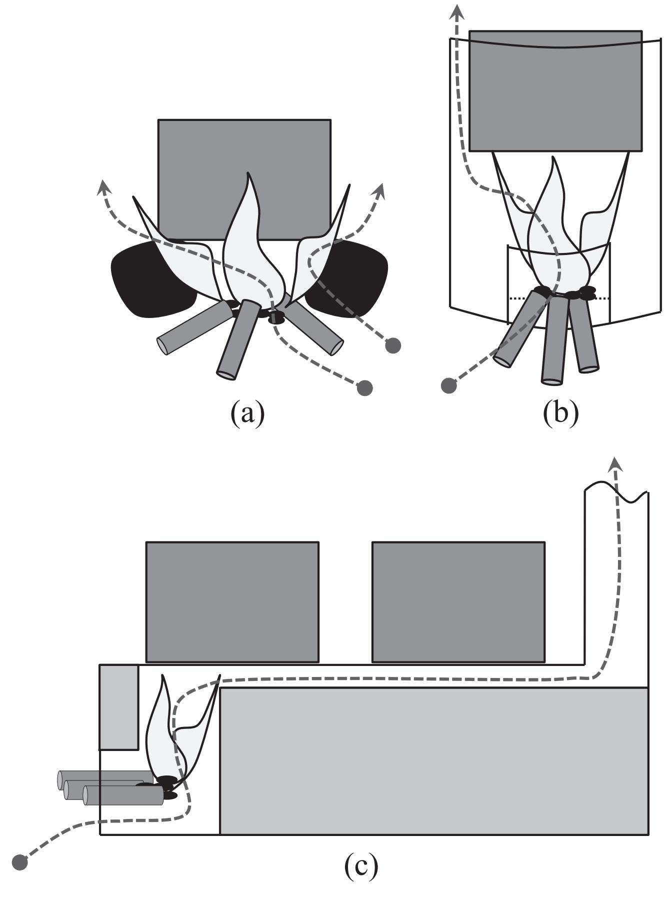

**Fig. 1.** Types of cookstoves: (a) open cooking fire, (b) shielded-fire cookstove, (c) enclosed fire with chimney.

## Cookstove models

Fig. 2 provides a schematic of a small biomass cookstove of the type used in nearly all numerical models. In general the goal of cookstove modeling has been to improve heat transfer efficiency of the cookstove system by examining the relationships between the combustion rate, excess air, geometry, and heat transfer. In all cases zonal models have been used to describe and couple the processes occurring within the three major zones of the cookstove system—the reacting fuel bed zone, the gas phase combustion zone, and the heat transfer zone around the cookpot.

Table 1 provides a summary of various cookstove modeling efforts over the past 30+ years. To understand past modeling work and the current state of progress towards a complete stove model, it is helpful to divide Table 1 into five groups of stove models. Four of these groups model the entire cookstove and are differentiated based on the coupling between the zones and how the gas phase reaction zone is modeled. The final group of models consists of models that address only a single aspect of cookstove design (e.g., heat transfer). The five groups are

1. Uncoupled models with no explicit gas phase combustion—these models do not include coupling between various zones of the stove in which results from one zone are used as inputs to a subsequent zone (De Lepeleire et al., 1981; Verhaart, 1982; Prasad et al., 1985; Baldwin, 1987). Rather, the boundary condition inputs (e.g., temperature and velocity) to each zone were assumed separately.
2. Coupled models with no explicit gas phase combustion—the Woodburning Stove Group at Eindhoven University over a period of years developed a set of models that couple solid phase combustion in the fuel bed together with buoyant flow in the flame zone to predict the heat transfer (Bussmann and Prasad, 1982; Bussmann et al., 1983; De Lepeleire and Christiaens, 1983;

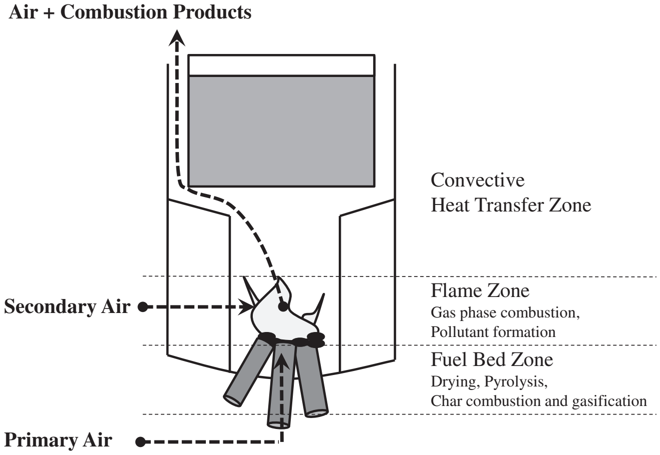

**Fig. 2.** Processes within a cookstove.