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A generalized heat-transfer model for shielded-fire household cookstoves

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ABSTRACT

This paper presents an experimentally validated steady-state heat transfer model of a shielded-fire, natural-draft biomass cookstove suitable for conceptual design of the small household cookstoves used in developing countries. The input variables for the model included 10 geometrical design variables, 2 material design variables, and 3 operating conditions. This model was validated using data from three previously published studies including 63 distinct combinations of the 15 design variables. The model results for thermal efficiency are within ±5% for 59 of the 63 designs and have an L2 norm error of 3.0%. Parametric variations of design variables can assist in the conceptual phase of design. In addition, the temperature and velocity profiles, location and magnitude of losses, and heat transfer contributions through various modes and regions of the pot provide sufficient detail to improve the understanding of a cookstove system and support detailed design.

Introduction and background

Approximately 2.7 billion people use solid biomass fuel in small stoves and three-stone fires to meet their household energy needs for cooking each day (IEA, 2010). This results in a number of adverse health, safety, community, and environmental effects including 4 million premature deaths each year, deforestation, and climate-changing emissions (Lim et al., 2012; Rehfuess, 2006; IEA, 2010; Bond and Sun, 2005). Recent projections indicate that use of biomass for cooking will increase and continue to be the dominant energy use in rural households through 2030 (IEA, 2010; Daioglou et al., 2012). For example recent studies in the West African Sahel found that in rural villages 98% of household energy needs are met with small household cookstoves (Johnson and Bryden, 2012a, 2012b). For these subsistence-level families, the cost of acquiring biomass fuel to meet their household energy needs represents a significant fraction of time and income (Rehfuess, 2006). As a result the design, manufacture, and distribution of clean, low cost, high efficiency household cookstoves has been identified by many governmental and non-governmental organizations as a critical need to improve the lives of the resource-poor while concurrently addressing millennium development goals and slowing climate change.

To meet this need a number groups have over the past thirty years worked to research, develop, and design household cookstoves, with more than 160 stove projects currently operating worldwide (Ruiz-Mercado et al., 2011). In spite of this the design of cookstoves today is primarily a heuristic trial and error process based on previous experience, engineering judgment, rules of thumb, and experiment. Currently there is no dominant design basis or established design algorithm for optimizing the efficiency of these devices, nor are there validated and accepted models or modeling guidelines to support the design process. In addition, there is no standard methodology for stove testing and reporting such that experimental data can be used for model development and validation. Over the past 30 years fewer than 30 journal articles have been written on the computational modeling of household biomass cookstoves, with the majority of these activities focusing on a single stove design, and few of these provide detailed experimental validation of the computational results (MacCarty and Bryden, 2015a). This paper presents an experimentally validated model capable of predicting the heat transfer performance of small cookstoves over a wide range of combustion conditions and geometric variables.

As shown in Fig. 1, a typical natural draft biomass cooking stove is conceptualized as being composed of the air handling system, the combustion chamber, the convective heat transfer region, the cooking pot, and the support structure and insulation. For modeling purposes, this system can be divided into three zones: the solid phase packed bed zone, the gas phase combustion or flame zone, and the heat transfer zone. In the packed bed, solid phase combustion includes heating and drying of the wood followed by pyrolysis and char combustion with primary air. In the flame zone, secondary air enters, is heated, and is supplied to the gas phase combustion. In the heat transfer zone, energy is lost through the stove walls, transferred to the pot via convection and

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Nomenclature

A	Area
c_p	Specific heat
D	Diameter
D_h	Hydraulic diameter
F	View factor
f	Friction factor
g	Gravity
H	Height
h	Specific enthalpy
$\tilde{h}$	Convective heat transfer coefficient
h_{fg}	Latent heat of vaporization
i	Counter, species flow in bed zone
j	Counter, incoming species in flame zone
k	Counter, total species flow of gases
$\tilde{k}$	Thermal conductivity
l	Counter, pressure losses
K	Pressure loss coefficient
$\dot{m}$	Mass flow
q	Heat transfer rate
R	Thermal resistance
T	Temperature
V	Velocity
W	Width
x	Segment length
β	Fuel bed size factor
ε	Emissivity
η	Thermal efficiency
ρ	Density
σ	Stefan-Boltzmann constant
ϕ	Radiation heat transfer adjustment factor
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
HHV	Higher heating value

Subscripts

air2	secondary air
amb	ambient
bed	fuel bed
c	combustion chamber
char	char
cond	conduction
cont	contraction
exp	expansion
ext	exterior wall
flame	flame
in	inlet
int	interior wall
pot	pot
rad	radiation
s	stove
sh	shield
v	volatiles
w	water
wall	wall

radiation, and exits as sensible losses. Fluid flow and the entrainment of excess air are driven by natural buoyancy, and is slowed by pressure losses due to friction throughout the various geometries of the flow path.

Three types of cookstove models have been developed by researchers: integral or zonal models, CFD models, and neural networks. Initial modeling efforts in the 1980s included algebraic and differential zonal models of open fires, shielded-fire stoves, and enclosed stoves, and focused on identifying equation sets for fluid flow and heat transfer throughout the system (De Lepeleire et al., 1981; Bussmann and Prasad, 1982; Bussmann et al., 1983; Bussmann and Prasad, 1986; Prasad et al., 1985). This was followed by investigation of specific regions such as wall losses or heat transfer correlations within a pot shield (Baldwin, 1987), or models of a specific stove design (Date, 1988; Kumar et al., 1990). After 2010, researchers continued to algebraically model specific stove designs (Agenbroad et al., 2011a, 2011b; Zube, 2010) and some incorporated solid and gas phase combustion rates and efficiency (Shah and Date, 2011). Several researchers have used CFD packages for stove modeling (Burnham-Slipper, 2007a, 2007b, 2008; Gupta and Mittal, 2010a, 2010b; Joshi et al., 2012; Ravi et al., 2002; Ravi et al., 2004) or for investigating heat transfer in specific regions of the stove (Wohlgemuth, 2010; Urban et al., 2002; McCorkle et al., 2003; Bryden et al., 2003). Hannai et al. (2006) used a neural network based model to predict the thermal efficiency of cooking pots based on experimental data for varying pot radii, height, degree of curvature, material conductivity, and flame diameter. This model was then validated using separate experiments and used to determine the effects of different parameters on efficiency. As a result, the optimal cooking pot could be designed for a given situation, similar to the present goal with cookstoves. A more detailed discussion of past biomass cookstove modeling efforts is presented in the recent review by MacCarty and Bryden (2015a).

Model development

As noted earlier, due to the lack of a suitable and accessible equation set, the current stove design process does not involve the assistance of computational modeling during the conceptual design phase, resulting in a missed opportunity for greater speed and accuracy in arriving at the most efficient design. To fill this gap, this paper presents a validated model for prediction of the steady-state thermal efficiency of a cylindrical, shielded-fire household cookstove with a natural draft air supply and flat-bottomed metal pot of diameter larger than the combustion chamber burning a continuous feed of wood sticks as fuel. Following a review of the literature, this general design was chosen as representative of the most common existing improved stove designs available today as shown by stove testing catalogs (Jetter et al., 2012; MacCarty et al., 2010) and in-field studies. While cookstoves using prepared fuels or forced draft may offer good performance, these will require modifications to modeling techniques and data for validation and are therefore left for a later time. The present model is based on a review of past modeling efforts of heat transfer and fluid flow, and validated using 63 data points of experimental results from three previously published studies catalogued in (MacCarty and Bryden, 2015b).

The model utilizes 15 operational, geometrical, and material design variables as inputs. The operating conditions include a constant given firepower, fuel heating value and as-received moisture content. The stove material and geometry are described by 12 design variables (Fig. 2):

- 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 shield (if included) and pot
- D_p—pot diameter
- H_p—height of water in the pot based on water volume
- D_s—stove combustion chamber body diameter
- k_s—stove body material conductivity (can account for multiple material layers via thermal resistance)
- H_{sh}—height of shield, if included