Computational Model of a Biomass Cookstove

Jennifer L. Jones[a], Ashok Gadgil[b,c], Carlos Fernandez-Pello[a]
[a]Department of Mechanical Engineering, University of California, Berkeley, CA 94720
[b]Dept. of Civil and Environmental Engineering, University of California, Berkeley, CA 94720
[c]Lawrence Berkeley National Laboratory, Berkeley, California 94720

1 Introduction

Indoor air pollution from the combustion of biomass fuels in cookstoves is of global concern because over 1/3 of the world's population uses biomass fuels for cooking and heating. Emissions from the combustion of biomass fuels include toxic gases such as carbon monoxide and particulates that pose serious health risks for families using cookstoves, especially women and children, leading to 1.6 million deaths globally per year [1]. Additionally, the aggregate amount of black carbon (soot) and greenhouse gases released to the environment from using cookstoves is a major concern for the global climate.

The objectives of this work were to build a simple numerical model of a biomass cookstove as a first step toward creating a comprehensive, computational model, and to determine the direction for future cookstove modeling work.

2 Background

Almost all of the cookstoves currently in operation are inefficient and heavily polluting. Most of the work on biomass cookstoves has been design through trial and error and experimentation. Hundreds of cookstoves are needed worldwide due to the diversity of cultural foods, cooking methods, power requirements, fuel types, and pot sizes. At this scale, improved cookstoves can't be designed and characterized in terms of performance through testing alone. A handful of research groups have begun modeling specific aspects of specific cookstoves, however a comprehensive, computational model of a biomass cookstove does not currently exist [2–4]. Additionally, ongoing testing has been performed to characterize improved cookstoves such as emissions testing of the Berkeley-Darfur Stove [5]. A comprehensive, computational model of a biomass cookstove would enhance scientific understanding of the underlying physical phenomena as well as be a tool for stove design and public policy. A computational model could be used to design and introduce cleaner and more efficient cookstoves worldwide, leading to decreases in health risks and environmental concerns from using cookstoves.

3 Model

An existing computational fluid dynamics (CFD) program, Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology, was used to develop the model. FDS solves the

Correspondence to: jennifer.jones@berkeley.edu

Figure 1: The Berkeley-Darfur Stove.

coupled governing equations of conservation of mass, species, momentum, and conservation of energy in three spatial dimensions on a rectilinear mesh. Spatial derivatives are discretized by finite differences with second-order accuracy. The equations are updated in time using an explicit second-order accurate predictor-corrector scheme. Turbulence is treated by the Smagorinsky form of Large Eddy Simulation (LES) [6]. The model was modified to account for pyrolysis of wood (rather than using a burner with a constant heat release rate) by using an Arrhenius reaction rate and properties for Douglas fir [7]. Combustion was modeled as a single step chemical reaction whose products were tracked by a two-parameter mixture fraction model.

3.1 Geometry

The geometry of the Berkeley-Darfur Stove (Figure 1) was used to create the cookstove in the model. The cookstove consists of a 12-sided, roughly cylindrical outer stove body, an inner semi-cylindrical firebox, and a perforated grate on which to hold the solid wood fuel. The stove body is approximately $22.5\,\mathrm{cm}$ from top to bottom and $25.5\,\mathrm{cm}$ in diameter. Air is drawn into the stove's combustion region by natural convection through two main intakes in the stove body and up through the holes in the grate. The main air intake into which the fuel is fed is at the front of the stove ($10\,\mathrm{cm}$ by $11\,\mathrm{cm}$). The secondary air intake is asymmetrically positioned opposite the primary air intake at the back of the stove below the level of the grate ($4.0\,\mathrm{cm}$ by $6.5\,\mathrm{cm}$).

3.2 Boundary Conditions and Input Parameters

The computational domain consisted of the stove geometry, the room around the stove, and boundary conditions. Ambient pressure and temperature boundary conditions were applied to the open planes comprising the computational domain. The floor was specified as a non-reacting surface at ambient conditions. Additionally, ambient pressure boundary conditions were applied to the stove air intakes and exit. The grid spacing was $5\,\mathrm{mm}$ and the time step was $0.01\,\mathrm{s}$. A small domain ($0.5\,\mathrm{m}$ in height) was initially used to save computational time since each simulation took approximately two weeks. Future work would involve a sensitivity study for mesh size supported by experimental validation.

Model input parameters and material properties including density, specific heat capacity, thermal conductivity, and emissivity were specified for Douglas fir, the mild steel stove body, stainless steel fire-

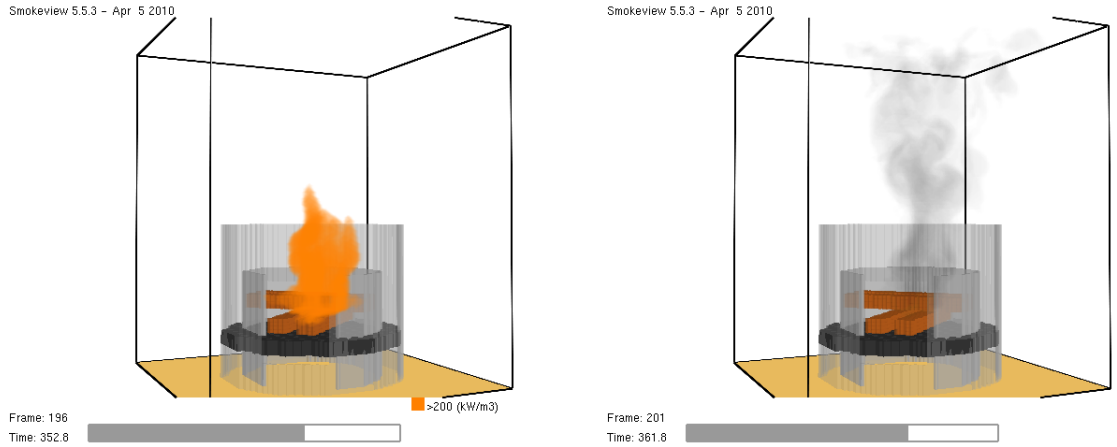

Figure 2: Model output of the (left) fire and (right) soot particles in the stove.

box, and cast iron grate. An external heat flux of $5\,\mathrm{kW/m^2}$ was applied to the surface of the wood to simulate using kindling to start the fire. An initial mass of $60.2\,\mathrm{g}$ of wood with an initial total surface area of $0.0256\,\mathrm{m^2}$ was modeled as a crib on the grate in the firebox. During pyrolysis 80% of the wood was converted to gas fuel and 20% of the wood was converted to char. For the Douglas fir fuel, $\mathrm{CH_{1.7}O_{0.74}N_{0.002}}$, soot yield and carbon monoxide yield were specified as $y_s = 0.03\,\mathrm{g/g}$ and $y_{CO} = 0.004\,\mathrm{g/g}$, and the heat of combustion was $\triangle H_F = 16400\,\mathrm{kJ/kg}$ [7]. Arrhenius reaction rate parameters were approximated by pre-exponential factor $A_o = 10\,\mathrm{E9\,s^{-1}}$ and activation energy $E_a = 1.3{\times}10^5\,\mathrm{kJ/kmol}$.

3.3 Output

Model output included visualization of the fire, soot particles, and flow field, and predictions of the mass loss rate of the pyrolyzing wood, the heat release rate from the combustion process, stove wall temperatures, air velocity, and mass flow rate of emissions out of the top of the stove. Both a baseline case and a case for which the stove and firebox walls were specified using adiabatic boundary conditions were computed. Results from the adiabatic case are presented here, representing an insulated stove and providing insight as to maximum achievable wall temperatures and heat transfer to a pot for cooking.

4 Results

Model output of the fire and soot particles are visualized using the Smokeview program (Figure 2). Every grid cell that has a heat release rate greater than $200\,\mathrm{kW/m^3}$ is colored orange to visually represent the flame. Predictions of the highest velocity flow out of the top of the stove is concentrated at the back of the stove in a symmetric crescent-like pattern at a velocity on the order of $1\,\mathrm{m/s}$ (Figure 3). Quantitative predictions included species mass flow rate of emissions out of the top of the stove (Figure 3) for a maximum heat release rate of approximately 8 kW and maximum stove body temperatures of approximately $T_w = 430 - 500\,^\circ\mathrm{C}$. The maximum stove wall temperatures were 200% higher for the adiabatic case, and the maximum emission rate of carbon monoxide, carbon dioxide, and soot out of the top of the stove increased by 50% for the adiabatic case when compared to the baseline.

We recognize that several limitations of FDS exist such as conformance to a rectilinear grid and mesh, and the inability to model complex chemistry such as the formation and oxidation of carbon monoxide

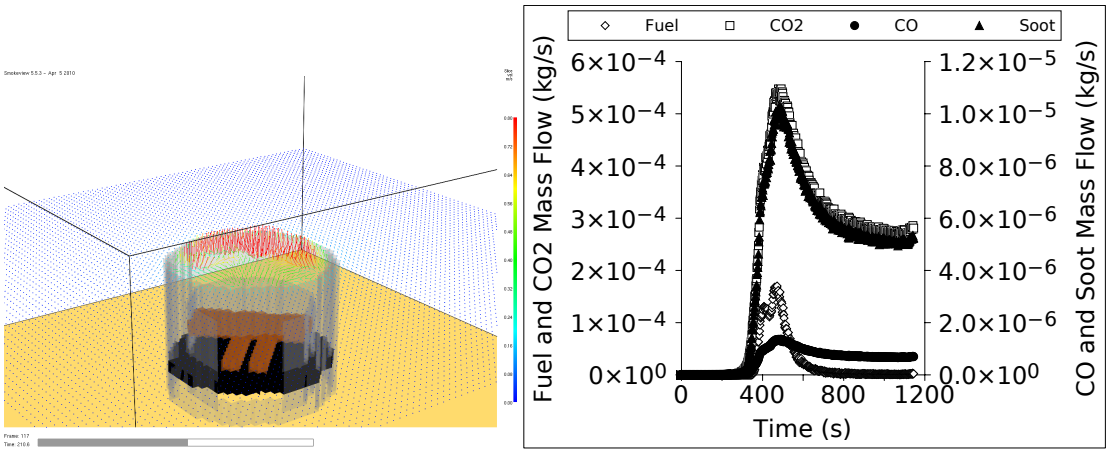

Figure 3: (Left) Model output in the horizontal plane at the height of the top of the stove depicting the flow field using velocity vectors to indicate the magnitude and direction of the flow. The highest velocity is on the order of $1\ \mathrm{m/s}$. (Right) Species mass flow rate of emissions out of the top of the stove.

emissions and soot. This preliminary model acted as a tool to help us define requirements for a next generation model.

5 Discussion and Future Work

A simple numerical model was created as a first step toward a comprehensive, computational model of a biomass cookstove. The model predicted the highest velocity (on the order of $1\ \mathrm{m/s}$) out of the top of the stove toward the back in a symmetric crescent-like pattern, and it is anticipated that the greatest convective heat transfer to a pot is along this region. Physically this makes sense because the air is being drawn into the stove through the primary air intake at the front of the stove due to natural convection. Model predictions of inlet air velocity and stove wall temperatures for the baseline case were in the ballpark when compared to preliminary experimental data obtained in the lab. Due to the limitations of the Fire Dynamics Simulator program, another existing CFD program would be more appropriate for modeling a biomass cookstove.

Future model refinement would be advantageous in the areas of formation and oxidation of emissions such as carbon monoxide and soot. Experimental data currently exist that we are not yet able to predict (Figure 4). The simplicity of the physical stoves mask the complexity of the underlying physical processes working interdependently within the stove. High frequency sampling (1 Hz) experimental data from Kirchstetter et al. of the Berkeley-Darfur Stove ([5]) show that emission rates of carbon monoxide and black carbon are correlated along two distinct branches (Figure 4). The model currently predicts one branch of the experimental data and predictions are an order of magnitude less than the data. Currently our approach is to specify a constant carbon monoxide and soot yield; it is our goal to incorporate these experimental results into a future model. Further model refinement could enable predictions of cookstove emissions and performance based on various cookstove input conditions to ultimately design more efficient, less polluting cookstoves. In addition to being a contribution to our scientific knowledge in the areas of combustion of biomass fuels, heat transfer, and fluid mechanics, a comprehensive, computational model of a biomass cookstove would be a valuable tool for researchers, designers, engineers, and those in public policy for various cookstove applications.

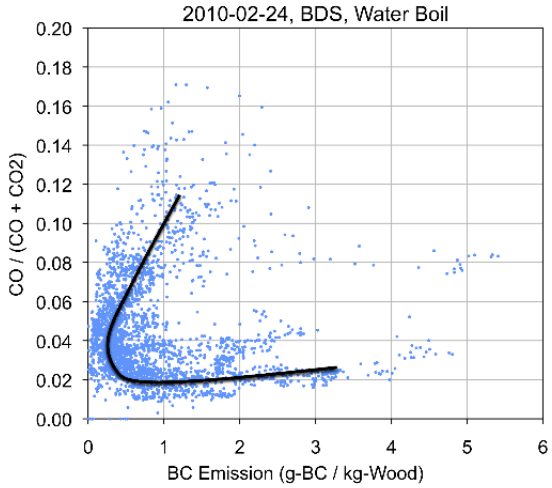

Figure 4: $\mathrm{CO}/(\mathrm{CO}+\mathrm{CO}_2)$ versus black carbon emission data from emissions testing of the Berkeley-Darfur Stove by Kirchstetter et al. [5].

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