Energy 157 (2018) 658–668

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A simplified combustion model integrated with a particle growth dynamic model for top-lit updraft cookstoves

Sameer Patel, Pratim Biswas*

Aerosol and Air Quality Research Laboratory, Center for Aerosol Science and Engineering (CASE), Department of Energy, Environmental, and Chemical Engineering, Washington University in St. Louis, One Brookings Drive, Brauer Hall, St. Louis, MO 63130, USA

ARTICLE INFO

Article history:
Received 22 February 2018
Received in revised form
9 May 2018
Accepted 30 May 2018
Available online 1 June 2018

Keywords:
Solid fuel cookstove
Particulate matter modelling
Emission factors
Emission rates
Cookstove metrics
Particle size distribution

ABSTRACT

Solid fuel stoves are used by over a third of the world's population for cooking and space heating. Efforts are being made to develop cookstoves with higher combustion and thermal efficiencies, but these efforts lack support of numerical models for predicting emissions that can be used in the design process. This work presents a simplified steady-state model to simulate combustion in a top-lit updraft (TLUD) cookstove integrated with a model for particle growth dynamics. The model incorporates the effects of cookstove operating parameters, specifically primary and secondary air fluxes and their temperatures and fuel composition (moisture, char, and volatile content) on various emissions and thermal characteristics of the cookstove, such as emission factors (EF), emission rates (ER), and size distribution of particulate matter. The results demonstrated that EF and ER do not necessarily follow the same trends, and therefore a lower EF might lead to a higher personal exposure. This raises serious concern over the high reliance on EFs as a metric to assess the performance of cookstoves. Emissions trends obtained from the model matched with the trends reported in previous studies. Sensitivity analyses demonstrated that a small variation in the cookstove operating parameters or fuel properties drastically changes emission.

1. Introduction

Cookstoves are used by more than a third of world's population, who burn solid fuels such as biomass and coal to fulfill their energy needs for cooking and space heating. Owing to low combustion efficiency, these cookstoves emit a range of products of incomplete combustion (PIC) leading to household air pollution (HAP) which adversely affects both human health and the environment [1–7]. Widespread transitioning from solid fuels to a cleaner fuel alternative such as electricity and natural gas seems to be challenging in the short term. Therefore, improving cookstove designs to enhance combustion and thermal efficiency, i.e., reduce cookstove emissions and fuel consumption per meal, seems to be a good approach in the interim.

There are several challenges that need to be addressed. Due to the variety of fuels used, there is no control over the fuel properties. Fuel stacking is prevalent, for reasons such as seasonal availability, price (in case households are buying fuel), and meal type [8–10], which results in a large variation in the physical and chemical properties of the fuel. These variations in fuel properties make designing a cookstove which performs consistently for all fuel types practically impossible. Moreover, even for the same fuel type, a small variation in its moisture content can significantly affect a cookstove's performance. Leavey et al. [11] demonstrated that increasing the moisture content of applewood from 1% to 6% increased particulate matter (PM) emissions more than 11 fold. Apart from fuel properties, inherent cookstove design features and variable operating conditions created by user habits also play critical roles in a cookstove's performance. For example, many improved cookstoves are forced draft, with provisions to control the air flow rate through the combustion zone that affect both its thermal and emission performance. Patel et al. [12] measured the particle size distribution of PM from a forced draft improved cookstove with different air flow settings and demonstrated that too high or too low an air flow increases PM emissions.

Owing to very high variations in fuel properties and operating parameters, the efficacy of improved cookstoves in reducing HAP has been very limited, with high fluctuations in their performance [4,13,14]. It is not feasible to account experimentally for so many variables with highly convoluted effects on combustion and emission characteristics of the cookstoves, especially when performance

* Corresponding author.
E-mail address: pbiwas@wustl.edu (P. Biswas).

https://doi.org/10.1016/j.energy.2018.05.196
0360-5442/

has shown high fluctuations even in controlled laboratory settings. Thus, simulating combustion in these cookstoves using computational tools can effectively develop our understanding of the performance of the cookstove and its dependence on fuel properties and operating conditions.

Limited work has been done to develop numerical models incorporating heat and mass transfer in cookstoves [15–17]. But MacCarty et al. [18] reviewed work done on biomass cookstoves in the last 30 years and reported a lack of numerical models. The authors also highlighted the reliance on experience and rule of thumb for designing cookstoves. Furthermore, in addition to the limited efforts to develop numerical models for cookstoves, there are no studies reporting modelling of a TLUD stove. Among the various types of improved cookstoves, TLUD are more efficient and less polluting, as demonstrated in previous studies [12,19–21]. Moreover, no model for cookstoves proposed so far includes PM emissions as an output [18].

This study presents an integrated combustion and particle growth dynamic model for top-lit updraft (TLUD) gasifier cookstoves. This model aims to fill a critical knowledge gap, i.e., numerical model for PM emissions from cookstoves. The steady-state model contains three sequential modules to simulate (1) the primary combustion zone as a co-current heterogenous system, (2) the secondary combustion zone for homogenous gas phase reactions, and (3) simultaneous natural dilution and particle growth. An improvement in the energy balance also addresses the shortcomings of the previous models proposed for solid fuel gasification and combustion. The effects of various cookstove operating parameters (primary and secondary air fluxes, and their temperatures), and fuel composition (moisture, char, and volatile matter content) on its performance was demonstrated by the simulation results.

2. Model description

Combustion in a gasifier cookstove occurs in a primary combustion zone and a secondary combustion zone (Fig. 1). In the primary combustion zone, which stretches along the length of the fuel bed, solid fuel is partially oxidized by the primary air, producing a combustible mixture of products of incomplete combustion (PIC) with CO, non-methane hydrocarbons (referred to as tar in this paper), CH_4, and H_2. These PIC are further oxidized by the secondary air at the top of the fuel bed, forming the secondary combustion zone. More details about the operating principle of the gasifier cookstoves are presented in our previous study [12].

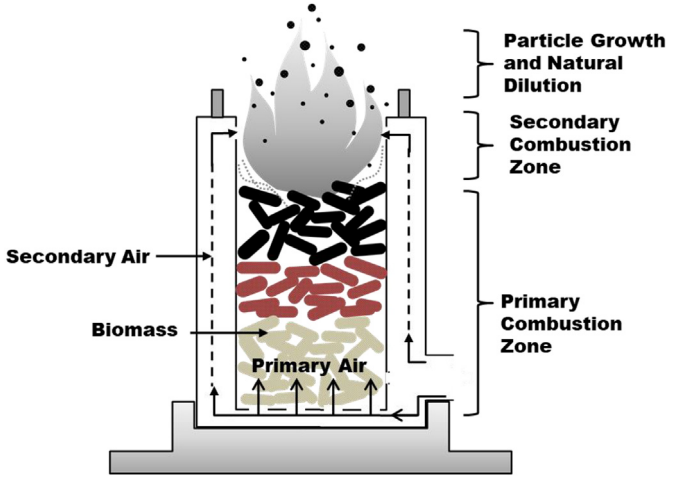

Fig. 1. Schematic of a top-lit updraft (TLUD) cookstove marked with the three stages modelled in this study (from bottom to the top): (1) primary combustion zone, (2) secondary combustion zone, and (3) simultaneous dilution of exhaust gas and particle growth.

Residential scale TLUD cookstoves are operated as batch reactors, i.e., the fuel bed height and temperature and emission profiles along it change during the cookstove operation. But instead of a transient model, a steady-state model is presented here to simulate combustion and particle formation in a TLUD gasifier stove as we sought to investigate the effects of various cookstove operating parameters and fuel properties on the performance of a TLUD stove. By assuming fuel enters the cookstove from the bottom at a rate equal to the net combustion rate of the solid phase, steady state modelling made it easy to study the above-mentioned effects.

The 1-D steady-state model was developed by integrating a three-part model working sequentially. The three models or parts in the sequence are (1) the primary combustion zone model, (2) secondary combustion zone model, and (3) particle growth dynamic model. The initial conditions for the first part, i.e., the primary combustion zone are user input, and the output serves as the input for the secondary combustion zone model whose output subsequently serves as the input of the particle growth model. The models for the primary and secondary combustion zone are described in Section 2.1, and the particle growth model is described in Section 2.2.

2.1. Combustion model

The combustion model is based on global chemical reactions, similar to what was done in previous studies [22,23]. Chemical and physical processes in the primary and secondary combustion zones can be broadly classified in four categories: (1) drying of biomass/fuel, (2) pyrolysis/devolatilization, (3) char gasification and oxidation, and (4) gas phase oxidation reactions. The kinetics of these reactions, taken from the literature [24–36], are summarized in Table 1.

Biomass devolatilizes to produce char and volatiles: a mixture of tar, CO, CO_2, CH_4, H_2, and H_2O (Eq. (1); reaction ID r_p). The char content of a fuel can be obtained from proximate analysis. The effects of the char to volatile matter ratio were investigated in this study, but the composition within the volatiles was kept constant at 6% CO, 13.5% CO_2, 15.5% H_2O, 0.4% CH_4, 0.3% H_2, and 64.3% tar by mass for all the cases simulated. This composition of the volatile matter was fixed based on the previously reported data for pyrolysis [37]. Tar produced from pyrolysis undergoes gas phase cracking (Eq. (2); reaction ID $r_{cracking}$) to produce CO, CO_2, CH_4, and H_2O, with mass fractions of 53.4%, 8.5%, 21.1%, and 17.0% respectively [37,38].

$$Dry\ Biomass \xrightarrow{p} char + (tar + CO + CO_2 + CH_4 + H_2O + H_2) \quad (1)$$

$$tar \xrightarrow{cracking} CO + CO_2 + CH_4 + H_2O \quad (2)$$

Char formed as a product of biomass pyrolysis usually has a high carbon content, and it is assumed to be 95% carbon, 2% hydrogen and 3% oxygen, i.e., $\alpha = 0.2526$, $\beta = 0.0237$, and $\gamma = 0.8013$ in Eqs. (3)–(5) [22]. Char is consumed by three heterogenous reactions, namely gasification by CO_2 (Eq. (3); reaction ID r_{g_CO2}), gasification by H_2O (Eq. (4); reaction ID r_{g_H2O}), and oxidation by O_2 (Eq. (5); reaction ID r_{g_O2}). Table 1 presents the kinetic models and relevant data for these three heterogenous reactions, which accounts for the mass transfer rate of the reactant gas to the char surface and the dependence on the char surface area. All heterogenous reactions (drying, pyrolysis, and char gasification via CO_2, H_2O, and O_2) were