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Steady state heat transfer modeling of solid fuel biomass stove: Part 1

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ABSTRACT

A steady state heat transfer model is developed to predict performance of biomass stove with varying operating (composition, particle size and moisture of fuel, air flow, ambient conditions) and design conditions (size, shape and material of combustion chamber, pot size). Model is validated for a commercial stove (*Harsha*) for test conditions. The burn rate and power delivery are estimated as 3.77×10^{-4} kg/s and 6.58 kW, respectively with air supply of 6.47×10^{-6} m^3/s resulting 1003 K flame temperature. The model is considered validated as the simulated results (24% efficiency and 17 min boiling time) are similar to experimental results reported in literatures. Major components of heat transfer from fuel combustion are primary air as 33%, unburned charcoal as 25%, cooking pot as 23%, others as 14% and combustion chamber as 6%. About 811 W of heat is used for self sustaining of combustion process. Highest share of primary air justifies the importance of exhaust heat recovery. The share of useful heat is 94.91% from heat of combustion and 5.08% from combustion chamber. The model is expected to be useful for new design, assessment of existing design and performance evaluation of any kind of solid fuel combustion device including biomass stove.

1. Introduction

Biomass is one of the primary fuels used all over the world. It is intensively used mainly for cooking, space heating and drying. Consumption of biomass as a primary fuel has remained unchanged with time and about 90% of rural population of India are still dependent on it to meet their basic fuel needs. It is also reported that the overall consumption of firewood has increased by about 7.5% in last decade. India, like most of the developing countries, uses traditional biomass fuels very inefficiently. This has created major economic, environmental and health threats [1].

Biomass cooking stove is the major thermal energy conversion device amongst the biomass fired technologies. The biomass stove is one of the primitive forms of thermal energy conversion devices. Even now, 38% of world populations are using biomass stoves to fulfill their cooking needs. In India about 66% of total population are still dependent on biomass for cooking purpose [2] using a variety of cooking stoves. There have been many different types of biomass cooking stoves which are classified according to (i) technology and nature of draft, (ii) type of combustion, (iii) applications or purpose, (iv) presence of chimney, (v) portability, (vi) material of construction, and (vii) fuel type [3]. In-depth analysis of most of the biomass cook stoves and their performance with relation to field test and laboratory tests are available in the literature [4–6]. Cook stove which works on the principles of direct combustion is preferred over the stove which runs with gasification, mainly due to better control on fire of the earlier. Interestingly, gasifier stoves are reported to result better performance in terms of fuel consumption. Thermal efficiency is sacrificed due to increase in thermal mass by addition of accessories like chimneys with additional benefits in terms of cleaner working space. Provision of forced draft enhances thermal efficiency necessitating additional power source [4].

Specific fuel consumption and thermal efficiency are two common parameters used to describe the thermal performance of stove. However, specific fuel consumption is considered more meaningful by users. In general, specific energy consumption of natural draft stove varies between 10 MJ and 25 MJ whereas a force draft stove operates between 10 MJ and 15 MJ [4].

The requirements of R&D on biomass cook stove with special focuses on (i) improvement of thermal efficiency, (ii) reduction of specific emission and (iii) ensured ventilation in India are emphasized while referring the Government of India sponsored initiatives to promote improved cook stove [6]. This is due the fact that with current trend of technology penetration, biomass cook stove will remain dominant particularly in rural India for quite some time.

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Along with the attempt to develop improved cook stoves, efforts are also being made to analyze the performance of existing stove through delineation and subsequent representation of their functioning through models [6–8]. Both steady and unsteady state stove models are used to predict and validate important parameters including maximum flame temperature, suction of combustion air, propagation of ignition front, moisture evaporation, devolatilization, pyrolysis and homogeneous and heterogeneous combustion reactions [7]. The stove simulation models also enabled to assess the thermal output, optimize design of stove and better selection of fuel type to maximize the performance [9].

The usefulness of precise stove models with appropriate representation of all heat transfer processes is realized. The practical applications of such detail heat transfer based models for gaseous fuels (LPG and PNG) to assist the better design of burners resulting enhanced thermal efficiency are already reported [10]. However, the detail heat transfer based model of biomass cook stove are limited and therefore, an attempt is made in this study to model relevant heat transfer processes in a biomass stove and so as to predict the its performance precisely. It is expected that the output of the work will be useful to optimize the design and operation for the best possible performance. Further, it will also be useful to identify the best suited fuel for an existing stove in terms of physical and chemical properties of fuel.

2. Assumptions for heat transfer analysis of a biomass stove

The operation of the stove can be viewed consisting of three distinct phases, *viz*., (i) initial transient state, (ii) operational stage and (iii) post operational stage. Heat transfer phenomena in all these three phases are different. In the present investigation the operational phase is considered for modeling the heat transfer processes with certain assumptions as discussed below.

In actual practice, a non-homogeneous fuel with varying air flow rate is expected to cause unsteady phase of operation in a stove. However, in the present investigation, such non homogeneity of fuel is ignored and flow of primary air is also expected to be uniform within an infinitesimal time interval. A finite mass of fuel is accommodated in batch within the stove. Such batch of fuel is considered to remain within the combustion chamber as layers with finite thickness combusted within the infinitesimal time interval. Operational phase starts with ignition when the top layer reaches the ignition temperature. There would be a temperature gradient below the top layer down towards the bottom layers in a decreasing pattern. In the present study, the top layer and the rest of the subsequent layers are considered differently. Thus, during an infinitesimal time interval, the steady state operation is considered and accordingly steady state heat transfer model is developed.

Non-homogeneity of biomass fuel might cause deviation of the fundamental assumption of propagation of ignition front uniformly from the top layer to the bottom layer of fuel. However, prediction of non-homogeneity amongst the layers of fuel is practically difficult and therefore, ignored for the present analysis. The assessment of instantaneous performance of the operation of a stove will not be affected with this assumption.

Major considerations of steady state modeling of biomass cooking stove are summarized below.

a) Atmospheric dry air with typical composition is used as oxidizer.
b) The mole ratio of nitrogen to oxygen of air is considered as 3.76 (mole fraction of oxygen and nitrogen is considered to be 21% and 79% respectively, neglecting presence of argon) as used normally for engineering calculations [11].
c) The argon present in air doesn't have any contribution during combustion of biomass and leaves along with products of combustion at elevated temperature [11]. In the present study, the thermodynamic properties of all the air components including Argon, both at inlet and outlet, are appropriately considered.
d) The fuel bed layer at ignition is at a height above the minimum bed height *i.e.* there is some amount of fuel burning on the bed beneath the ignition layer.
e) Temperature of all the segments *viz*., (i) fuel bed, (ii) combustion chamber inner wall (iii) combustion chamber outer wall, (iv) flame, (v) pot bottom, (vi) contents of pot and (vii) ambient are different but steady.
f) The flow of primary air is maintained according to the required conditions of the igniting layer and governs by fuel bed height and geometries of fuel particle.
g) The complete combustion of fuel is achieved.
h) The fuel is distributed in honeycomb pattern.
i) For validation of the model a commercial biomass stove is considered, details of which are obtained from the published literature as shown in Table 1.
j) Woody biomass with less than 30% moisture content is used for combustion.

3. Development of heat transfer model of biomass cook stove

During a standard combustion process, the ignition of the top layer would result a flame from the volatile fraction of the biomass, whereas the fixed carbon portion keeps on igniting. These two components are considered as primary sources of thermal energy. Heat generated from the flame is transferred to (i) primary air, (ii) pot bottom, (iii) combustion chamber wall and (iv) surrounding. Part of the heat from flame also transfers towards the bottom layers of the fuel bed for sustainability of the ignition process. Moreover, the residual heat carried away by the flue gas is also transferred to the pot bottom and the combustion chamber. Simultaneously, the heat from the combustion of fixed carbon available in the top layer is also transferred to the (i) fuel layers beneath it, (ii) combustion chamber, (iii) primary air and (iv) pot bottom. Residual heat of fixed carbon is remained in the left over charcoal. A portion of the heat released towards the downward fuel bed during combustion of both volatiles and fixed carbon is utilized to evaporate fuel moisture of the downward layers. All of these components of heat are modeled using the known principles of heat transfer which are presented in Fig. 1 and Table 2.

Table 1
Performance parameters and characteristics of a biomass stove.

Sl. No.	Parameters	Source
Performance parameters of a stove		
1	Ignition front velocity	[7]
2	Burn rate	[6]
3	Power delivery	[6]
4	Efficiency of stove	[8]
5	Time to boil	
Other stove characteristic parameters		
1	Physical dimensions	[3]
2	Stove material	
3	Mode of primary air supply	
4	Fuel type	
5	Applications	
6	Number of pots	
7	Portability	
8	Combustion type	