Reduced model for combustion of a small biomass particle at high operating temperatures

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HIGHLIGHTS

▶ A model for a small biomass particle combusting at high temperatures is presented.
▶ The model accounts for three processes: heating up, pyrolysis and char combustion.
▶ Heating up and pyrolysis stages are formulated using an integral method.
▶ Char combustion process is modeled according to shrinking core approximation.
▶ The dominant process during combustion of particle is found to be pyrolysis.

ARTICLE INFO

ABSTRACT

The aim of this work was to demonstrate a model for a spherical biomass particle combusting at high temperatures with reduced number of variables. The model is based on the observation that combustion of a small particle includes three main phases: heating up, pyrolysis, and char conversion. It is assumed that the pyrolysis begins as soon as the particle surface attains a pyrolysis temperature, yielding a char front, moving towards the center of particle as time passes. The formulation of the heating up and pyrolysis phases is based on an integral method which allows describing the energy conservation with an ordinary differential equation. The char combustion model is according to the shrinking core approximation. Model validation is carried out by comparing the predictions with experiments of sawdust particles taken from the literature, and with computations of partial differential equation-based models. Satisfactory agreement is achieved between the predictions and experimental data.

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1. Introduction

The primary aim of the present paper is to establish a reduced but efficient mathematical model for predicting the main characteristics of a combusting single biomass particle at the conditions of biomass combustors, where particles in the order of less than millimeter undergo a complete thermo-chemical conversion process at a high reactor temperature (>1100 K). Experimental observations (Saastamoinen et al., 1993, 2010) indicate that the combustion of biomass particles at the above mentioned conditions consists of three main stages including heating up, pyrolysis, char oxidation and gasification. Fig. 1 depicts the trends of mass loss and temperature histories of a dry biomass particle during the above three distinguished stages. Of course, depending upon process conditions, pyrolysis and char consumption phases may partly overlap. Description of various physical and chemical processes involved in combustion of a single biomass particle is given in an earlier paper (Haseli et al., 2011a).

Detailed numerical models (Wurzenberger et al., 2002; Peters, 2002; Bruch et al., 2003; Porteiro et al., 2006, 2007; Lu et al., 2008; Yang et al., 2008; Yin et al., 2010; Haseli et al., 2011a) presented in the literature allow prediction of time and space evolution of various process parameters (e.g. biomass and char densities, porosity, temperature, velocity of gaseous flow within the pores, pressure gradient, mass fraction of various gaseous species such as H_2O, CO, CO_2, tar) during combustion of a single particle. These comprehensive models provide a useful tool to get a deeper inside into the complex physics of thermo-chemical conversion of single biomass particles. Nevertheless, simulation using these models would be at the expense of significant computational time and programming efforts since they consist of a set of strongly coupled partial differential equations based on the conservation of mass, momentum and energy.

In an earlier work (Haseli et al., 2011a), a one-dimensional model for combustion of single biomass particle was presented, as the

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Nomenclature

A	pre-exponential factor, kg/m^2 s Pa		t_R	duration of thermal penetration movement from the surface to the center of particle, s
c_p	specific heat, J/kg K		t_{pini}	time of commencement of pyrolysis at the surface of particle, s
E	activation energy, kJ/kmol			
f_v	stoichiometric volatiles/oxygen ratio		Y	mass fraction
h	convective heat transfer coefficient, W/m^2 K		*Greek letters*	
k	thermal conductivity, W/m K		α	thermal diffusivity, m^2/s
k_d	mass transfer coefficient, m/s		Δh_{Com}	specific enthalpy of char oxidation reaction, kJ/kg
M	molecular weight, kmol/kg		Δh_p	specific enthalpy of pyrolysis, J/kg
m	mass, kg		Δh_v	specific heat of volatiles combustion, J/kg
$\dot{m}''$	decomposition rate per unit surface area, kg/m^2 s		ε	emissivity
$\dot{m}''_C$	char burning rate per unit surface area, kg/m^2 s		ω	$=\rho_C/\rho_B$
$\dot{m}''_v$	volatiles mass flux per unit surface area, kg/m^2 s		ρ	density, kg/m3
P	pressure, Pa		σ	Stephen–Boltzmann coefficient, W/m^{2}K^4
q''	heat flux, W/m^2		ϕ_1	a time dependent coefficient in Eqs. (7) and (8)
q''_{net}	net heat flux at particle surface, W/m^2		v	oxygen stoichiometric coefficient in reaction (*I*)
R	particle radius, m		*Subscripts*	
R_g	universal gas constant, J/mol K		0	initial condition
r	spatial coordinate, m		∞	surrounding condition
r_c	char depth, m		B	biomass
r_t	thermal penetration depth, m		C	char
T	temperature, K		g	gas phase
T_p	pyrolysis temperature, K		mix	gaseous mixture at the particle surface
T_{sR}	surface temperature at the time t_R, K		s	surface
t	time, s			

first phase of our research work concerned with understanding the key sub-processes involved in biomass combustion at the conditions corresponding to those found in real furnaces. Now, the question of interest is how one may establish a reduced model based on the basic conservation laws in order to predict the main characteristics of combustion of a single biomass particle pertaining to the conditions of biomass combustors? In recent decades, some researchers have tried to come up with simple models for predicting the general behavior (in terms of conversion time, mass loss and temperature histories such as those shown in Fig. 1) of a combusting particle. It is not intended to perform an extensive review here, so only the results of some interesting modeling approaches presented in the literature are briefly discussed below.
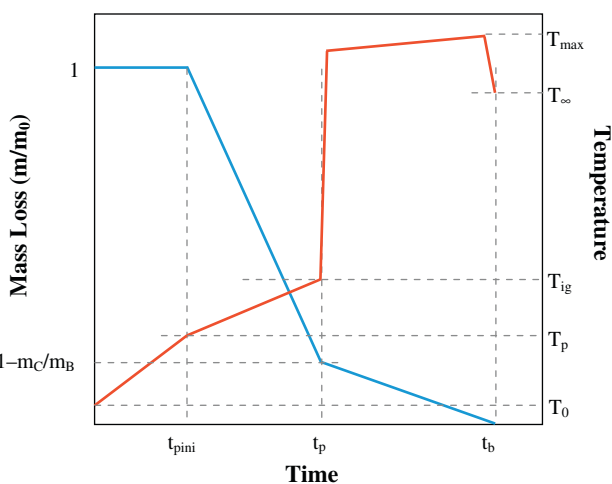

Fig. 1. Schematic representation of mass loss (blue line) and temperature (red line) histories during combustion of a thermally intermediate particle. The three distinguished phases include (1) heating up ($0 \leqslant t \leqslant t_{pini}$), (2) pyrolysis ($t_{pini} < t \leqslant t_p$), (3) char combustion and gasification ($t_p < t \leqslant t_b$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The simplified model introduced by Saastamoinen et al. (1993) assumes that devolatilization takes place uniformly inside particle, and that the char residue burns as a shrinking particle. The model accounts for simultaneous pyrolysis and char combustion with partial combustion of volatiles in the mass transfer boundary layer surrounding the particle. This model has recently been modified (Saastamoinen et al., 2010) by accounting for a conductive thermal resistance within the particle and introducing an average particle temperature. In the modified model, the heat of char combustion, an endothermic heat of pyrolysis, and the heat received from the flame sheet around the particle are taken into account.

Ouedraogo et al. (1998) described a shrinking core model for predicting the combustion of a large wet wood particle. The formulation was based on the experimental evidence that large wood specimens inserted into a hot convective environment lose mass over a relatively thin layer at the particle exterior, whereas the interior region remains almost undisturbed. They assumed that when the fuel element is inserted into a hot convective environment, its surface temperature will instantly reach a quasi-steady state condition with an initial formation of a char layer. They further assumed that the combustion of char occurs in a diffusion-controlled regime, and the total mass of solid fuel represents carbon.

A further interesting reduced model of a single large wood particle relevant to particles used in fluidized and fixed bed combustors and gasifiers was presented by Thunman et al. (2002). The model accounts for the temperature gradients inside the particle, the release of volatiles, shrinkage, and swelling. It divides the particle into four layers: moist virgin wood, dry wood, char residue, and ash. The development of these layers is computed as a function of time. The model treats the particle in one dimension and the conversion of particle is described by heat and mass transfer to the surface of particle.

He and Behrendt (2011) developed a method by combining a volume reaction model and front reaction approximation for predicting the combustion of a large moist biomass particle. In their model, drying and char oxidation are simplified as a front reaction