



Characterization of biomass combustion at high temperatures based on an upgraded single particle model



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HIGHLIGHTS

- High temperature rapid biomass combustion is studied based on single particle model.
- Particle size changes in devolatilization and char oxidation models are addressed.
- Time scales of various thermal sub-processes are compared and discussed.
- Potential solutions are suggested to achieve better biomass co-firing performances.

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ABSTRACT

Biomass co-firing is becoming a promising solution to reduce CO₂ emissions, due to its renewability and carbon neutrality. Biomass normally has high moisture and volatile contents, complicating its combustion behavior, which is significantly different from that of coal. A computational fluid dynamics (CFD) combustion model of a single biomass particle is employed to study high-temperature rapid biomass combustion. The two-competing-rate model and kinetics/diffusion model are used to model biomass devolatilization reaction and char burnout process, respectively, in which the apparent kinetics used for those two models were from high temperatures and high heating rates tests. The particle size changes during the devolatilization and char burnout are also considered. The mass loss properties and temperature profile during the biomass devolatilization and combustion processes are predicted; and the time-scales of particle heating up, drying, devolatilization, and char burnout are compared and discussed. Finally, the results shed light on the effects of particle size on the combustion behavior of biomass particle.

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1. Introduction

Biomass is a sustainable fuel that can deliver a significant reduction in net carbon emissions when compared with fossil fuels, and environmental and social benefits could also be expected [1]. However, due to high volatile contents and low energy densities, the combustion properties of biomass are significantly different from those of coals, limiting the biomass substitution ratios in co-firing boilers. Currently, biomass co-firing levels are mostly below 5% on energy basis, while more than 10% biomass substitution are seldom commercialized [2,3]. An efficient biomass co-firing solution is therefore required to attain

large percentages of biomass co-firing in existing pulverized coal boilers.

When entering a pulverized-fuel flame, biomass particles are rapidly heated to a final temperature in the range of 1400–1600 °C at a rate of approximately 10⁴ °C/s [4,5]. However, most common analysis based on TGA is not able to determine the accurate kinetics of biomass combustion at real furnace conditions, due to the relatively low temperatures (<1000 °C) and low heating rate (<1 °C/s) [5]. Therefore, there is a clear lack of a suitable biomass combustion model with feasibility of representing more faithfully a true boiler or furnace condition, in which biomass particles are heated rapidly to high temperatures. Accordingly, the study of biomass thermal behavior at real combustion conditions is the first step in understanding biomass combustion behavior and possibility of large percentage co-firing with coals.

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Nomenclature

Symbols

A	pre-exponential factor in Arrhenius expression (1/s)
C	carbon content (% dry ash free basis)
D	diffusion rate coefficient (m^2/s)
d_p	particle diameter (m)
E	activation energy (J/kmol)
f	fraction of heat absorbed by solid residuals
k	kinetic constant ($\text{kg}/\text{m}^2 \text{ Pa s}$)
\dot{k}	thermal conductivity ($\text{W}/\text{m K}$)
m	mass (kg)
MC	moisture content (%)
n	reaction order (-)
P	pressure (Pa)
r	particle radius (m)
R	gas universal constant $8.3143 \text{ J}/(\text{mol K})$
S	char specific surface (m^2/kg)
T	temperature (K)
X	mass conversion (-)
α	particle size evolution exponent (-)

Subscripts

B	biomass
$Char$	char
dry	drying
$devo$	devolatilization
exp	experimental
g	gas phase
M	moisture
mod	modeled
ox	char oxidation
p	particle
s	solid remains
$vola$	volatile
w	furnace wall
0	initial value

Biomass combustion has widely been studied based on a single particle model [6–18]. For example recently, Porteiro et al. [13] employed a single particle model to investigate the biomass thermal conversions, considering both intra-particle combustion and extra-particle transport processes to describe the thermal deration of biomass particles; the impacts of structure changes on the heat transfer properties of wood was also studied in their further work [12]. To study the combustion properties of a woody biomass particle, Haseli et al. [14] upgraded a one-dimensional particle model accounting for particle heating-up, devolatilization, char oxidation, and gaseous phase reactions. Lu et al. [15,16] reported the effects of particle size and particle shape on the devolatilization and combustion performance of biomass employing a one-dimensional particle model and discussed with their experimental results. Yang et al. [18] studied combustion characteristics of a wide range of sizes biomass (10 μm to 20 mm) using same single particle modeling approaches.

This paper studies biomass combustion properties at a high temperature and high heating rate that are similar to the conditions in a real furnace. A computational fluid dynamics (CFD) combustion model of a single biomass particle is employed, and the existing devolatilization and char oxidation models are upgraded to study high-temperature rapid biomass combustion behavior. Biomass devolatilization reaction rate and the amount of released volatiles are governed by a two-competing-rate model, considering the swelling properties of biomass particle during its devolatilization process. The biomass char oxidation rate is controlled by both kinetics and oxygen diffusion combining an empirical method for predicting particle size changes with char burnout. The mass loss properties and temperature profile during the biomass devolatilization; and combustion processes are predicted, and the timescales of particle heating up, drying, devolatilization, and char burnout are discussed.

2. Fuel and method

2.1. Fuel and kinetics

The studied woody biomass is palm kernel shell (PKS), and its proximate and ultimate properties are listed in Table 1. The apparent kinetics of devolatilization and char oxidation of biomass have

been previously determined by a series of tests in an isothermal plug flow reactor (IPFR) [4,5], as also presented in Table 1.

2.2. Modeling approach

This numerical study concerns exposing a woody biomass particle in a high temperature furnace; the oxidizing agent, air, comes from one side of the furnace, and the flue gas flows out from the other side. The whole combustion process includes the particle heating-up, drying, devolatilization, and char oxidation. Once exposed in the high temperature furnace, the biomass particle is heated up by the surrounding furnace wall and oxidizing agent via radiation and convection, resulting in a rise in the surface temperature of the biomass particle. The released heat is then transferred from the particle surface to its center by conduction. The moisture and volatile matter are released once the particle temperature has reached a reactive temperature, and the drying and devolatilization rates depend on the particle temperature.

The amount of released volatile matter depends on the fuel type and devolatilization conditions, and the volatiles mainly consist of gaseous hydrocarbons at high temperatures. However, due to the complexities in the chemical reactions, the kinetics of individual gaseous species released during the devolatilization are still not well understood. It is reasonable to represent the volatile matters by a single virtual material, although in practice it contains many kinds of species [19]. A surface reaction model is applied for the char oxidation process that takes place on the particle surface, while an empirical shrinking model is applied to simulate the particle size changes.

2.3. Mass and energy conservations

The equations presented below describe the evolution of solid components including dry biomass and char. Ash is not considered in this simulation due to its small amount.

$$\frac{\partial \rho_B}{\partial t} = -k_{devo} \rho_B \quad (1)$$

$$\frac{\partial \rho_{Char}}{\partial t} = (1 - v_{Vola}) k_{devo} \rho_B - k_{ox} \rho_{Char} \quad (2)$$

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