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A study to investigate pyrolysis of wood particles of various shapes and sizes

Yawei Chen, Kumar Aanjaneya, Arvind Atreya*

Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA

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ABSTRACT

Pyrolysis of centimeter-scale wood particles of various sizes and shapes needs to be understood to determine their burning rate and life. Such particles may be thought of as firebrands, which are a major reason for spotting ignition in wildland and wildland-urban interface fires. The burning lifetime of firebrands controls the maximum distance they can travel to cause spotting. To understand and model this, experiments are done in a vertical tube furnace with wood particles of different sizes and shapes. For computations, two classes of shapes, prolate and oblate ellipsoids, were chosen to represent the arbitrary geometry of such particles. Prolate ellipsoids include shapes ranging from thin needles to spheres, whereas, oblate ellipsoids include shapes ranging from thin disks to spheres. The choice of these smooth shapes, while facilitating expedient computations also enables the coverage of wide ranges of particle shapes and surface area to volume ratios (SVR). Model simulations show satisfactory agreement with relevant literature and experimental data. Particle aspect ratio (ϵ, the ratio of minor and major axes), SVR, and equivalent radius (R_e) are used to define the particle geometry. Mass loss and center temperature profiles are presented and discussed. It is shown that with the decreasing of aspect ratio, wood particle decomposes faster and the final char fraction becomes smaller. A power-law based correlation between conversion time (t_{con}) and SVR is derived and verified against experiments. Further, it is shown that an increase in the SVR enhances the production of tar and decreases the yield of char while leaving the yield of gas mostly unaffected.

1. Introduction

Spotting ignition by lofted firebrands is one of the most significant mechanisms of fire propagation in wildland and wildland-urban interface (WUI) fires. The phenomenon of spotting may be broken down into three consecutive events: (i) generation of various size and shape firebrands by the fire, (ii) transportation of firebrands and (iii) ignition of the fuel present at the landing site [1]. During the last several decades, a substantial amount of research has been done to investigate the behavior of firebrands with particular regards to firebrand trajectory, lifetime, fire transport models, degradation of burning firebrand, etc. [2-5]. Clearly, research on firebrands requires the understanding of a broad range of phenomena. To understand the production of firebrands, the pyrolysis and degradation of trees and shrubs in the main fire need to be investigated. While important, we will not focus on this topic. Firebrands, so generated, typically have irregular shapes and sizes, resulting in various particle surface areas to volume ratios (SVR). SVR is critical for heat and mass transfer rates, which affects the pyrolysis rate and hence the burning rate. This is the main focus of this study because it determines the lifetime of firebrands. This study focuses on the pyrolytic behavior of wood particles of various shapes and sizes.

Influence of shape and size on pyrolysis of wood particles has been investigated previously. Lu et al. [6] conducted an experimental and theoretical investigation of three types of particles: flake-like, cylinder-like and near-spherical. They concluded that both particle shape and size affect the product yield distribution, particle conversion time and mass loss rate. However, with regards to the variety of shapes studied, this work was limited. Additionally, the two-stage wood pyrolysis model used by the authors fails to predict the peak in center temperature, which is observed in experiments. Di Blasi et al. [7] studied the effects of particle size and density on packed bed pyrolysis of wood. They reported an effect on the conversion time due to variations in heat and mass transfer rates (caused by varying physical properties) but negligible effect on the yield and composition of lumped product classes. In this study, even though different sizes and shapes of particles were used, the effective shape remained unchanged since particles were packed in a cylindrical holder made of stainless steel mesh. Other experimental and theoretical investigations of the effects of particle shapes and sizes on the pyrolysis of biomass particles are limited in the range of particle geometry used [8-10.]

One of the most basic issues to be settled is: What should the geometry of the wood particles be for computations that would be

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* Corresponding author.
E-mail address: aatreya@umich.edu (A. Atreya).

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Nomenclature

A_i	pre-exponential constant (s^{-1})
B	permeability (m^2)
C	specific heat (J/kg/K)
C_p	specific heat at cons. pres. (J/kg/K)
d	pore size (m)
e	emissivity
E_i	activation energy (J/mol/K)
f	focal length (m)
h	heat transfer coefficient ($W/m^2/K$)
k_i	reaction rate (s^{-1})
L_2	semi-major axis (m)
M	molecular weight (kg/mol)
P	pressure (Pa)
P_0	ambient pressure (101,300 Pa)
P_t	tar partial pressure (Pa)
P_g	gas partial pressure (Pa)
Q	heat generation (W/m^3)
R	univ. gas constant (8.314 J/mol/K)
R_e	equivalent radius (m)
S	mass generation ($kg/m^3/s$)
SVR	surface area to volume ratio (m^{-1})
t	time (s)
t_{con}	pyrolysis conversion time (s)
T	temperature (K)
T_f	furnace temperature (K)
T_g	gas temperature (K)
V	flow velocity (m/s)
Y	solid mass fraction

Greek

α, β, η	spheroidal coordinate
ξ, ϕ, ω	spheroidal coordinate
ϵ	aspect ratio
ε	porosity
ν	degree or extent of pyrolysis
Δh	heat of pyrolysis(J/kg)
λ	thermal conductivity (W/m/K)
μ	viscosity (kg/m/s)
ρ	density (kg/m^3)
σ	Stefan's constant ($5.67 \times 10^{-8} W/m^2/K$)

Subscripts

a	virgin solid
c, c_2	char char generation reaction
g, g_2	gas generation reaction
is	intermediate solid
s	surface
t	tar
v	volatiles
w	initial virgin solid

representative of different shapes and enable correlating the experimental results? Baum and Atreya [11] developed a quasi-steady burning model in prolate and oblate coordinates to study vaporizing of solids. However, charring solids, which are practically more important, were not examined. Carmo and Lima [12] studied moisture diffusion inside oblate spheroidal solids. These studies conclude that prolate and oblate spheroids can be used to represent wood particles of various shapes and sizes. For aspect ratio (ϵ, the ratio of minor and major axes) equal to unity, both of the aforementioned ellipsoids represent spheres while for the limiting case of ($\epsilon \to 0$) the former reduces to a thin needle while the latter to a thin disk (see Fig. 3). These smooth shapes are convenient for numerical computation and cover all possible particle shapes and SVR. It must be pointed out that these ellipsoids have smooth surfaces while wood particles found in forests are expected to have sharp and jagged edges. However, these edges are anticipated to be quickly pyrolyzed leaving behind smooth shapes for continued pyrolysis. The biggest advantage offered by these shapes is that only two parameters, namely L_2 (semi major axis) and ϵ determine the specific geometry. This results in a considerable simplification of the geometric description of infinitely different shapes having varying degrees of irregularity while accounting for almost all possibilities.

2. Modeling and experiments

Wood pyrolysis involves complex physical and chemical processes such as heating of virgin wood, initiation of primary pyrolysis reactions that release volatiles and form char, mass transport of volatile products by convection and diffusion, condensation of some volatiles in the cooler parts followed by secondary reactions, convection of gas species at the surface of biomass particles, etc. A wood pyrolysis model developed earlier by the authors [13], as schematically shown in Fig. 1, was applied in the present study. The model accounts for the endo/exothermic behavior observed in the experiments and it also predicts the mass loss and temperature profiles very well. In this model, biomass decomposes to gas (non-condensable volatiles), tar (condensable hydrocarbons) and intermediate solid when heated. Tar experiences secondary decomposition into gas and char while the intermediate solid change into char. Major assumptions made in the mathematical model are: (1) Volatiles and solid are in local thermal equilibrium, so temperature and temperature gradients are the same for both. (2) Volume and shape of charring solid remain constant during pyrolysis, i.e., no shrinkage. (3) Volatile gases have ideal gas behavior. (4) Dry biomass particles are used, thus there is no evaporation of water.

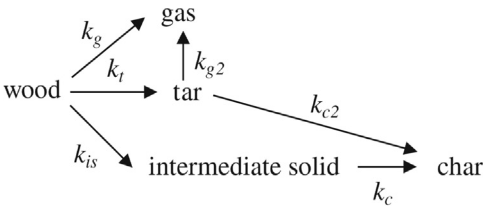

Fig. 1. Reaction scheme for wood pyrolysis.

2.1. Prolate and oblate coordinate systems

A prolate spheroid results from rotating a two-dimensional ellipse about the symmetry axis on which the foci are located (Fig. 2). The prolate spheroidal coordinates are related to Cartesian coordinates through the following transformations [14].

$$\begin{aligned} x &= f\sinh\alpha\,\sin\beta\cos\omega \\ y &= f\sinh\alpha\,\sin\beta\sin\omega \\ z &= f\cosh\alpha\,\cos\beta \end{aligned} \tag{1}$$

Where, f is the focal length, $0 \le \alpha \le \infty$, $0 \le \beta \le \pi$, $0 \le \omega \le 2\pi$. Surfaces of constant α form prolate spheroids while those of constant β generate hyperboloids of revolution. An alternative form is defined by:

$$\xi = \cosh\alpha,\ \eta = \cos\beta,\ \phi = \omega \tag{2}$$

Where, $1 \le \xi \le \infty$, $-1 \le \eta \le 1$, $0 \le \phi \le 2\pi$. Then we have