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A numerical investigation of the influence of radiation and moisture content on pyrolysis and ignition of a leaf-like fuel element

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ABSTRACT

The effects of thermal radiation and moisture content on the pyrolysis and gas-phase ignition of a solid fuel element containing high moisture content were investigated using the coupled Gpyro3D/FDS models. The solid fuel has dimensions of a typical *Arctostaphylos glandulosa* leaf which is modeled as thin cellulose subjected to radiative heating on one side. We incorporated a five-step extended Broido-Shafizadeh reaction model for thermal degradation, moisture evaporation, and pyrolysis of cellulose in Gpyro3D. The solid-phase model was successfully validated against published data. Ignition of the modeled leaf-like fuel element at three initial moisture contents (5%, 40%, or 80%) exposed to a 1500 K radiant source was simulated. Lower moisture content resulted in earlier onset of pyrolysis and ignition resulting in higher solid and gas phase temperatures. Local moisture evaporation and temperature rise were observed in all three cases and a significant amount of moisture remained in the sample during ignition. The numerical results suggested that moisture content not only affected the process of pyrolysis, but also influenced the ignition and gas phase combustion of the solid fuel.

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1. Introduction

Fire burns in vegetation in many regions of the world; humans and ecosystems have evolved with this process [1]. While wildland fire is a natural and desired ecological disturbance in many areas, it can also pose a threat to human life, property, and natural resources in other areas. The vegetative fuel for wildland fire is a combination of the living plants and their dead, cast-off foliage and branches. These fuel components have a variety of characteristics which influence the pyrolysis, ignition, and subsequent spread of a wildland fire [2]. Of particular importance to fire is the quantity of water contained in the fuel components. Living plants actively regulate the water contained in their plant cells while the dead components absorb and desorb water passively like a sponge [3]. Plants have adapted various strategies to conserve water and the moisture content (mass of water expressed as percentage of dry mass) which ranges from approximately 50% to greater than 300% for some succulents. In contrast, the moisture content of dead fuels ranges from 0% to about 40% at saturation.

Many wildland fires burn in the elevated foliage and branches (collectively known as the plant's crown) of living vegetation. These crown fires burn in coniferous forests in the Northern Hemisphere, eucalyptus forests in Australia, and in shrubland types such as California chaparral, Chilean mattoral, and Mediterranean maquis. In the United States, data used to parameterize the operational model used by wildland fire managers to predict fire spread originated from experiments using dead woody material on the ground. Other empirical models have been developed from observed fire spread in live fuels in the field [4–9]. These operational models [4–6] can predict fire spread rate well for the conditions under which the data were collected, but they are less accurate for other conditions.

Because of its empirical-physical nature, the model developed by Rothermel [4] does not explicitly model heat transfer modes as do other models, e.g., Pagni and Peterson [10] and Balbi et al. [11]. In a spreading wildland fire, fuel particles such as leaves and branches in unburnt vegetation are exposed to convective and radiative heat transfer. The relative importance of external heat transfer mechanisms in wildland fire has been a subject of debate for several decades and recent work has begun to demonstrate the importance of convective heating [12,13]. According to McAllister et al. [14], when thermal radiation alone was used as a heating mode, an addition pilot source was required to cause ignition. However, according to Pickett et al. [15], when the convective heating was used; achieved by subjecting the vegetation to hot gases, it caused ignition without the aid of a pilot. Preliminary results of a current study have shown that a thermal

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Greek symbols

$\boldsymbol{\tau}$	stress tensor
χ_s	fraction of consumed fuel mass converted to soot
Δ	filter width
δ	cell size (m)
$\dot{\omega}'''$	volumetric source term (kg/m^3 s)
ϵ	emissivity
ν_α	reaction stoichiometric coefficients
ν_t	eddy viscosity (m^2/s)
ϕ	generic scalar
ψ	porosity
ρ	density (kg/m^3)
K	permeability (m^2)
ν	kinematic viscosity (m^2/s)

Variables

$\dot{Q}'''$	heat of reaction in the solid phase (W/m^3)
$\hat{\mathbf{s}}$	unit vector in the direction of radiation intensity
$\hat{\mathbf{x}}$	position vector (m)
Pr_t	turbulent Prandtl number
$\mathrm{R_u}$	universal gas constant (J/mole K)
Sc_t	turbulent Schmidt number
A	pre-exponential factor (1/s)
C_s	smagorinsky constant
c_p	specific heat capacity (J/kg K)
D	diffusivity (m^2/s)
E	activation energy (kJ/mol)
G	normalized filter kernel function
G_m	specific gravity of moist wood
h	sensible enthalpy (J/kg)
H_c	heat of combustion (J/kg)
h_c	heat transfer coefficient (W/m^2 K)
I	radiation intensity (W/m^2 sr)
k	thermal conductivity (W/m K)
M_c	fuel moisture content
M_s	number of solid phase reactions
n_α	number of species
P	background pressure (Pa)
p	perturbation pressure (Pa)
P_g	gas phase pressure within the solid fuel (Pa)
T	temperature (K)
t	time (s)
U	total radiation intensity in the gas phase (W/m^2)
W	molecular weight (kg/kmol)
x	distance (m)
Y	mass fraction
y	distance (m)
z	distance (m)
$\mathbf{J}$	diffusion flux of gas phase species (kg/m^2 s)
$\mathbf{J}_\alpha^g$	diffusion mass flux (kg/m^2 s)
$\mathbf{n}$	unit vector normal to the boundary surface
$\mathbf{S}$	strain rate tensor
$\mathbf{u}$	velocity vector (m/s)
$\dot{\mathbf{m}}''$	convective mass flux (kg/m^2 s)

Superscripts

∞	ambient (as in the solid–gas interface)
sgs	subgrid stress

Subscripts

α	solid/gas phase species
d	destruction
F	fuel species
f	formation
g	gas phase within the solid fuel
s	solid phase

radiation flux of 50 kW/m^2 will not ignite live fuels. Gallacher *et al.* [16] and Engstrom *et al.* [17] used a radiant panel with a maximum heat flux of 50 kW/m^2 as the heating source to study effects of radiative heating on the leaves of manzanita (Arctostaphylos glandulosa), oak (Quercus berberidifolia), ceanothus (Ceanothus crassifolius) and chamise (Adenostoma fasciculatum) species. They reported that no ignition or visible flame was observed when the radiation alone was the source of heating, so the radiant source was dropped from the experiment in order to determine the burning characteristics using the flat flame burner convective source. The experiments measured the surface and tip temperature history of the leaf using IR camera and type-K thermocouple respectively. Ignition criteria used in these experiments was based on a visible flame through a video data obtained at 30 frames per second using PCI 1411 (NI)DAQ card and Hi-8 camcorder.[1]

When a solid fuel is heated to a sufficiently high temperature, it undergoes thermal degradation [18]. For the purpose of modeling, thermal degradation is assumed to occur in two sequential steps. The first step is pyrolysis, which is usually an endothermic process that breaks down vegetation composed of cellulose, hemicelluloses, and lignin into low molecular mass gases (pyrolyzates), tars, carbonaceous char and mineral ash. The second step is combustion wherein the gases are ignited and oxidized resulting in a visible diffusion flame. Ignition criteria have been defined for solid phase, the gas phase or combined solid and gas phases [19]. In the present study, we defined ignition based on the gas phase. Critical mass flux and heat release rate (HRR) define ignition. A single value of heat release rate, as a reasonable criterion for ignition, has been proposed [20,21]. We defined ignition as the time at which the HRR exceeded 200 kW/m^3 in the gas phase over the surface of cellulose element. Any value above this critical value would mean an active flame observed in the simulation over the solid fuel.

The solid fuel (vegetation) consists of different polymers present in the organic fraction of the fuel and the mass of the inorganic fraction is generally very low in most fuels ($<$ 5%). Hemicellulose, cellulose and lignin comprise 20–40%, 40–60%, and 10–25% of biomass, respectively [2,22,23] with cellulose being the main component [22]. The interest in modeling fire and using biomass as an energy fuel has resulted in a large body of work characterizing biomass fuels and their thermal degradation over the past 60 years [18, 24–27]. Chemical reactions of cellulosic materials exposed to high temperature sources can be broadly classified as primary and secondary reactions. Primary reactions are concerned with the degradation of the cellulosic fuel into char and numerous volatile products whereas secondary reactions are those undergone by primary volatile products [28]. The first kinetic models were proposed in the 1960s by Kilzer and Broido [29], Chatterjee and Conrad [30] and Shafizadeh [31], and form the basis of more recent kinetic models. Cellulose is assumed to decompose through two parallel or competitive reactions [29,31]. Results obtained by Broido [29] and other investigators [30,31] indicated that lower heating rates yield more char. Below approximately 280 °C, the formation of char is assumed favored while above this temperature, formation of tar is assumed favored. The reason for this assumption could be due to the predominant depolymerization reactions associated to the breakage of glycosidic bonds [32].

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