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Experimental and numerical studies characterizing the burning dynamics of wildland fuels

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ABSTRACT

A method to accurately understand the processes controlling the burning behavior of porous wildland fuels is presented using numerical simulations and laboratory experiments. A multiphase approach has been implemented in OpenFOAM, which is based on the FireFOAM solver for large eddy simulations (LES). Conservation equations are averaged in a control volume containing a gas and a solid phase. Drying, pyrolysis, and char oxidation are described by interaction between the two phases. Numerical simulations are compared to laboratory experiments carried out with porous pine needle beds in the FM Global Fire Propagation Apparatus (FPA). These experiments are used to support the use and the development of submodels that represent heat transfer, pyrolysis, gas-phase combustion, and smoldering processes. The model is tested for different bulk densities, two distinct species and two different radiative heat fluxes used to heat up the samples. It has been possible to reproduce mass loss rates, heat release rates, and temperatures that agree with experimental observations, and to highlight the current limitations of the model.

1. Introduction

Many experimental studies on wildland fuel flammability are conducted at small bench scale or even at microscopic scale, such as Thermogravimetric Analysis (TGA) [1,2] and Differential Scanning Calorimetry (DSC) [3–5] to understand the physical and chemical processes involved during the decomposition of the fuel when heated [2,6]. While it is difficult to perform large scale experiments, to maintain repeatable and fully controlled environments [7–9], and to monitor all the dynamics involved, the use of numerical models becomes essential. Different types of models exist and they are used to predict wildfires. They are either based on empirical correlations [10–13], simplified models [14,15], or detailed computational fluid dynamics (CFD) models [16–18]. These CFD models are often used to study large fires [18–21], in which many parameters and complex submodels are included in order to provide satisfactory results.

The first aim of this study is to perform experiments at an intermediate scale that is small enough to maintain a controlled environment, and large enough to be comparable to real fire conditions. Therefore, experiments are conducted in the FM-Global fire propagation apparatus (FPA) [22,23], which allows repeatable conditions to be achieved, and to monitor temperature, heat release rate (HRR), gas production and mass loss rates (MLR) as in [24–26]. In tests performed for the present work, temperature was measured inside the fuel bed to make sure that the heat transfer (radiation and convection) is modeled correctly during the heating phase, before ignition, where there is no flame radiation and soot oxidation yet. Measurements of gas production allow determining the HRR, which indicates how the energy is released. Finally, mass loss indicates the degradation rate, including evaporation, pyrolysis and char oxidation. Mass loss is also linked to the burning rate, which, along with the surrounding conditions, will affect the HRR, flame height and the burning rate. Separately, spectral measurements have been done for dead pine needles under a wide spectrum (0.25–20 μm) to determine the effective absorptivity of the fuel under the FPA halogen lamps, used to heat up the samples.

Numerical simulations are then conducted to mimic the same experimental conditions to verify how well the model behaves and to understand its limitations. The numerical approach is based on the multiphase model [17,27–29] that was implemented in OpenFOAM [30] and called ForestFireFOAM. The latter is built following

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Nomenclature

a	Thermal diffusivity
c	Speed of light
C, C'	Convective heat transfer constants
C_{EDC}, C_{diff}	EDC model coefficients
C_p	Specific heat capacity
D	Equivalent diameter
E_{pyr}, E_{char}, E_{vap}	Energy activation for pyrolysis, charring and vaporization
Gr	Grashof number
h_p	Planck's constant
I	Spectral intensity
J	Irradiance
K	Air thermal conductivity
K_{pyr}, K_{char}, K_{vap}	Pre-exponential factors for pyrolysis, charring and vaporization
k_b	Boltzmann constant
k_{SGS}	Sub grid scale kinetic energy
m, m'	Convective heat transfer coefficient constants
n, n'	Convective heat transfer coefficient constants
Nu	Nusselt number
Pr	Prandtl number
$Q^{(S)}_{CONV}, Q^{(S)}_{RAD}$	Convective and radiation heat transfer source terms
$\dot{q}''_{FPA}$, $\dot{q}''_{surf}$	Imposed and corrected heat fluxes
$\dot{q}''_{net}$	Net energy received by the solid fuel
R	Ideal gas constant
Re	Reynolds number
s	Stoichiometric O_2/C mass ratio
T, T_s	Gas and solid phase temperatures
T_r	Radiation source temperature
$Y^{(S)}_{DRY}$, $Y^{(S)}_{H_2O}$	Mass fraction of dry pine needle and water in solid phase
Y_F, Yo_2	Fuel and oxygen mass fraction

Greek symbols

α_{eff}	Effective absorptivity
α_{flam}	Effective absorptivity from flame
α_{char}	Char absorptivity
β_{char}	Char correction factor
Δ	LES filter size
Δh_{char} Δh_{pyr} Δh_{vap}	Reaction heat for charring, pyrolysis and vaporization
ε_{SGS}	Sub grid scale dissipation rate
λ	Wavelength
ρ	Gas density
ρ_s	Fuel (solid phase) density
σ	Stefan–Boltzmann constant
σ_s	Surface to volume ratio (SVR)
ϕ_g, ϕ_s	Volume fraction of gas, solid phase
χ	Convective heat transfer coefficient
$\dot{\omega}'''_F$, $\dot{\omega}'''_{CHAR}$, $\dot{\omega}'''_{PYR}$, $\dot{\omega}'''_{VAP}$	Volumetric rate of gas combustion, pyrolysis, charring, and vaporization

the structure of FireFOAM, a LES code for fire modeling [31]. The multiphase formulation is used to include the process of degradation of the forest fuel by drying, pyrolysis and heterogeneous combustion, and to simulate it by assuming a volumetric reaction rate. This approach was not yet implemented neither in OpenFOAM, nor in FireFOAM. Consequently, part of this study has been dedicated to the implementation of this new model. The multiphase approach was introduced by Grishin [27], in which he presented an extensive review of the work conducted in USSR in the 1970s and 1980s on wildland fires. Grishin's model was the first to incorporate kinetics to describe pyrolysis, combustion, and hydrodynamics through a fuel bed using a multiphase approach. Thermal equilibrium was initially assumed between gas phase and solid phase and the equations were averaged over the height of the forest canopy to simplify the formulation. Later, Larini et al. [28] presented the bases of the multiphase formulation for a medium in which a gas phase and N solid phases in thermal non-equilibrium are treated individually along with some one-dimensional applications. A detailed review of these models are presented in [32].

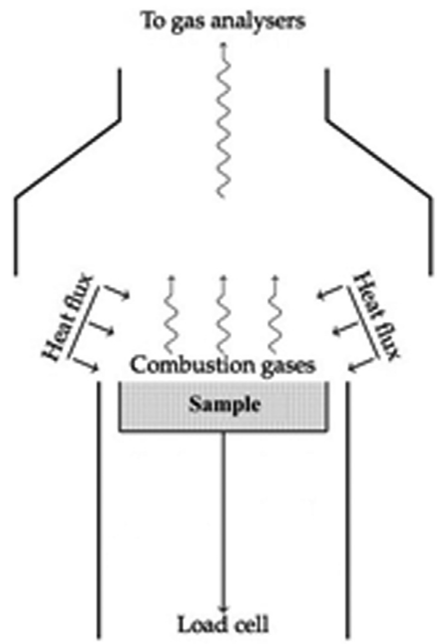

Fig. 1. Overview of the Fire Propagation Apparatus (FPA).

The multiphase model includes the Navier–Stokes conservation equations [33] for radiative and reactive multiphase medium. The closure models, or submodels that are used for degradation, heat transfer, combustion, and radiation are typically applied to simulate large-scale wildfires in complex environments. However, they were obtained from micro- and small- scale laboratory experiments using very different conditions than the ones where they are often applied in the literature [20,27,28,34,35]. These submodels are described and examined hereafter at intermediate scale. The multiphase model is tested with experiments using fuel beds with different bulk densities that are representative of litter conditions. Two distinct North American species with different surface to volume ratios are burnt at two different heat fluxes imposed by the FPA heaters. Pine needle beds are used as a reference fuel because they are well characterized in the literature [36] and they allow obtaining repeatable fuel bed properties under laboratory settings. Moreover, pine needle beds often accumulate on forest floor and near structures in the Wildland Urban Interface (WUI), increasing the fire risk [37].

2. Experimental configuration

2.1. FPA experiments

Experiments were performed with the FM Global Fire Propagation Apparatus (FPA), which provides controlled and repeatable conditions [24,26] (Fig. 1), such as the ability to produce a constant incident radiative heat flux. No forced flow was applied in this study, only natural convection was allowed through the porous