Combustion and Flame 190 (2018) 12–24

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Framework for submodel improvement in wildfire modeling

Mohamad El Houssami[a], Aymeric Lamorlette[b], Dominique Morvan[c], Rory M. Hadden[a], Albert Simeoni[c,*]

[a] The University of Edinburgh, Edinburgh EH9 3JL, UK
[b] Aix-Marseille Université, CNRS, CentMarseille, M2P2, 13451 Marseille, France
[c] Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609, USA

ARTICLE INFO

Article history:
Received 13 May 2016
Revised 24 August 2016
Accepted 28 September 2017

Keywords:
Multiphase
Forced flow
Porous
LES

ABSTRACT

An experimental and numerical study was carried out to assess the performance of the different submodels and parameters used to describe the burning dynamics of wildfires. A multiphase formulation was used and compared to static fires of dried pitch pine needles of different bulk densities. The samples were exposed to an external heat flux of 50 kW/m^2 in the FM Global Fire Propagation Apparatus and subjected to different airflows, providing a controlled environment and repeatable conditions. Submodels for convective heat transfer, drag forces, and char combustion were investigated to provide mass loss rate, flaming duration, and gas emissions. Good agreement of predicted mass loss rates and heat release rates was achieved, where all these submodels were selected to suit the tested conditions. Simulated flaming times for different flow conditions and different fuel bulk densities compared favorably against experimental measurements. The calculation of the drag forces and the heat transfer coefficient was demonstrated to influence greatly the heating/cooling rate, the degradation rate, and the flaming time. The simulated CO and CO_2 values compared well with experimental data, especially for reproducing the transition between flaming and smoldering. This study complements a previous study made with no flow to propose a systematic approach that can be used to assess the performance of the submodels and to better understand how specific physical phenomena contribute to the wildfire dynamics. Furthermore, this study underlined the importance of selecting relevant submodels and the necessity of introducing relevant subgrid-scale modelling for larger scale simulations.

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1. Introduction

Understanding the burning behavior of wildland fuels is essential to develop a complete understanding of wildfire spread. For the last decades, numerous studies have been attempted to better describe the fire dynamics of solid fuels [1–3], including polymers [4–8], cellulosic materials [9,10], and different species of wood [11–14]. The transfer of this knowledge to describe the burning behavior of wildland fuels, which are natural polymers, is not trivial because they differ from classical solid fuels, as they often consist in highly porous media where the solid phase is very small compared to the gas phase. The main challenge arises from the porous nature of the fuels and its coupling with the transient surrounding environment, which strongly influences the heat transfer, degradation rates, and the burning dynamics [15]. Indeed, during combustion of a highly porous bed, the heat captured by the solid phase is a result of the energy balance from the flame feedback by radiation and from the fresh air entrained into the fuel layer by convection, but also reacting with the pyrolysis products and with the char residue. As a consequence, these homogeneous and heterogeneous combustions contribute to transfer energy to the solid phase. This behavior is different from that observed for solid fuels for which the radiative and convective contributions of the flame can be considered to be transferred into the solid by conduction [16]. This highly porous configuration is typically found in pine needle beds, which are often found on the forest floors. They can typically be found accumulated near structures in the Wildland Urban Interface (WUI), increasing the fire risk [17]. As the need to understand the burning dynamics of wildland fuels is a matter of great urgency in order to improve wildfire assessment tools, many studies have been performed over the last decades. Among those, Dimitrakopoulos and Papaioannou [18] used the cone colorimeter to determine the ignition time and the flammability of typical Mediterranean forest fuels and proposed four flammability classes. Schemel et al. [19] reported a calorimetric study of pine needle beds using the FM Global Fire Propagation Apparatus (FPA), during

* Corresponding author.
E-mail address: asimeoni@wpi.edu (A. Simeoni).

https://doi.org/10.1016/j.combustflame.2017.09.038
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Nomenclature

C	Convective heat transfer constants
C_D	Drag force coefficient
D	Equivalent diameter
E_{CHAR}	Energy activation for char oxidation
$\overline{HRR}$	Average Heat Release Rate
k	Air thermal conductivity
K_{CHAR}	pre-exponential coefficient for char oxidation
m_0	Initial mass
m, n	Convective heat transfer coefficient constants
Nu	Nusselt number
P	Pressure
Pr	Prandtl number
$Q_{char}^{(s)}$	Char oxidation source term
$Q_{CONV}^{(S)}$	Convective heat transfer source term
R	Ideal gas constant
Re	Reynolds number
T, T_s	Gas and solid phase temperatures
U	Velocity
Y_{O_2}	Oxygen mass fraction

Greek symbols

α_g, α_s	Volume fraction of gas and solid phases
Δh_{CO}, Δh_{CO_2}	Heat of combustion of CO and CO_2
ρ	Gas density
σ_s	Surface to volume ratio
φ	Split function
$\varphi_{char}^{(S)}$, $\varphi_{DRY}^{(S)}$, $\varphi_{H_2O}^{(S)}$	Mass fraction of char, dry pine and water in solid phase
χ	Convective heat transfer coefficient
$\dot{\omega}_{char}'''$, $\dot{\omega}_{pyr}'''$, $\dot{\omega}_{vap}'''$	Volumetric rate of charring, pyrolysis, and vaporization

which it was shown that calculating the heat release rate (HRR) by means of calorimetry for pine needles can be reinforced by the use of mass loss rate and by knowing the heat of combustion in well ventilated test conditions. Bartoli et al. [20] demonstrated that permeability drives the burning dynamics in porous beds and that the energy released increases with permeability. Additionally it was shown that for a given permeability, the fuel species have an influence on times to ignition and duration of flames. Mindykowski et al. [21] conducted experiments in the same experimental setup to investigate the piloted ignition time of litters composed of oven Mediterranean pine species and kermes oak leaves.

The porous bed can be described through CFD modeling using a multiphase formulation that allows the fire rate of spread (ROS) [22–24], and temperature field to be estimated [25]. For instance, Padhi et al. [26] described the flow field generated due to the steady burning of a shrub using the multiphase formulation. Velocity and temperature profiles were analyzed in the continuous flame region and thermal plume region and it was highlighted that the porous nature of the shrub affects air entrainment into the shrub, thus affecting the nature of the fire plume. Hence, it is important to evaluate the model's capabilities to simulate air entrainment and air mixture in the fuel bed. The use of the multiphase formulation is not new, it has been applied in numerous studies to describe the interaction between the atmospheric boundary layer with a canopy problems using isothermal flows [27–33]. However, the multiphase formulation is usually applied to simulate large-scale wildfires under complex conditions without thoroughly pre-validating or verifying if the selected submodels (i.e. the closure models) are well adapted to the fuel conditions and to the surrounding environment in which they are used, and if they allow the relevant physics to be captured [15,34–37]. For instance, degradation rates are provided from TGA analysis at a much smaller scale (microscopic) than reality [15], and drag coefficients are derived from wind tunnel tests for simple geometries at ambient temperatures [38]. In a recent study, Hoffman et al. [39] evaluated crown fire spread rate using FIRETEC [40] and WFDS [41] (both include a multiphase approach) and compared the results to a compilation of wildfire observations in North American forests [42]. It was noted that the ability to test the model was limited by a lack of environmental and fuel data such as errors associated with point-to-point comparison, which is a limitation of large scale fires. This aspect is essential because the rate of spread predictions from detailed physics-based models are sensitive to small variations in both the spatial pattern of the fuels and the environment. Therefore, this study recommended further assessment of detailed physics-based models, particularly by providing additional data regarding fuel and environmental characteristics (i.e. wind). This is why it is necessary to establish a framework tailored to the development of fire modeling with the multiphase approach. It allows to study elementary aspects of the problem and to gradually move towards complexity (by changing the fuel or environmental properties). This methodology follows a building block approach to model development and facilitates a better understanding of forest fuel flammability and of its corresponding fire dynamics.

This study includes well documented fire experiments that are conducted in a controlled environment, providing precise measurements for different fuel and ambient conditions, to quantify the influence of the parameters on the models numerical predictions. As these conditions change, some parameters and submodels in the numerical model are no longer valid and need to be adjusted. This parametric study is often overlooked at larger scale due to the excessive uncertainties caused by the large variations of fuel properties (i.e. special distribution, fuel moisture content), the unstable wind (i.e. gusts), and the strong coupling between submodels, which makes it impossible to pinpoint exactly which submodel is not behaving physically. In this study, experiments were undertaken in the FM Global Fire Propagation Apparatus (FPA) [43], similarly as in [19,20] where it was demonstrated to proving repeatable conditions. Pine needle beds of varying porosity were subjected to a radiative heat and various values of airflows to observe the burning behavior under different conditions relevant to wildfire spread. Pine needle beds were used as a reference fuel because they allow repeatable fuel bed properties under laboratory settings. Mass loss rates, heat release rates, flaming times, gas emissions, and temperature fields were used to compare the experiments to the simulations. Particular attention was given to forced flow conditions - extending previous work on natural convection [44] - because in wildfires, the flow is usually highly unstable and not well defined. Consequently, local variations in the flow can have important impacts on the local fire regime. However, the flow is controlled and can be well characterized in the FPA. This framework, with the appropriate modifications supports the development of large scale CFD modeling by providing inputs and indications for the necessary subscale modeling.

2. Methods

2.1. Experimental details

Experiments were conducted by burning beds of pine needles in the FPA [43] (Fig. 1). The apparatus provides a controlled environment with respect to air flow and repeatable, uniform heating conditions. Samples were exposed to a radiative heat flux of 50 kW/m^2 applied to the top surface of the sample, throughout the entire experiment mimicking a strong flame feedback from a larger fire surrounding the sample. This value of received heat flux

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