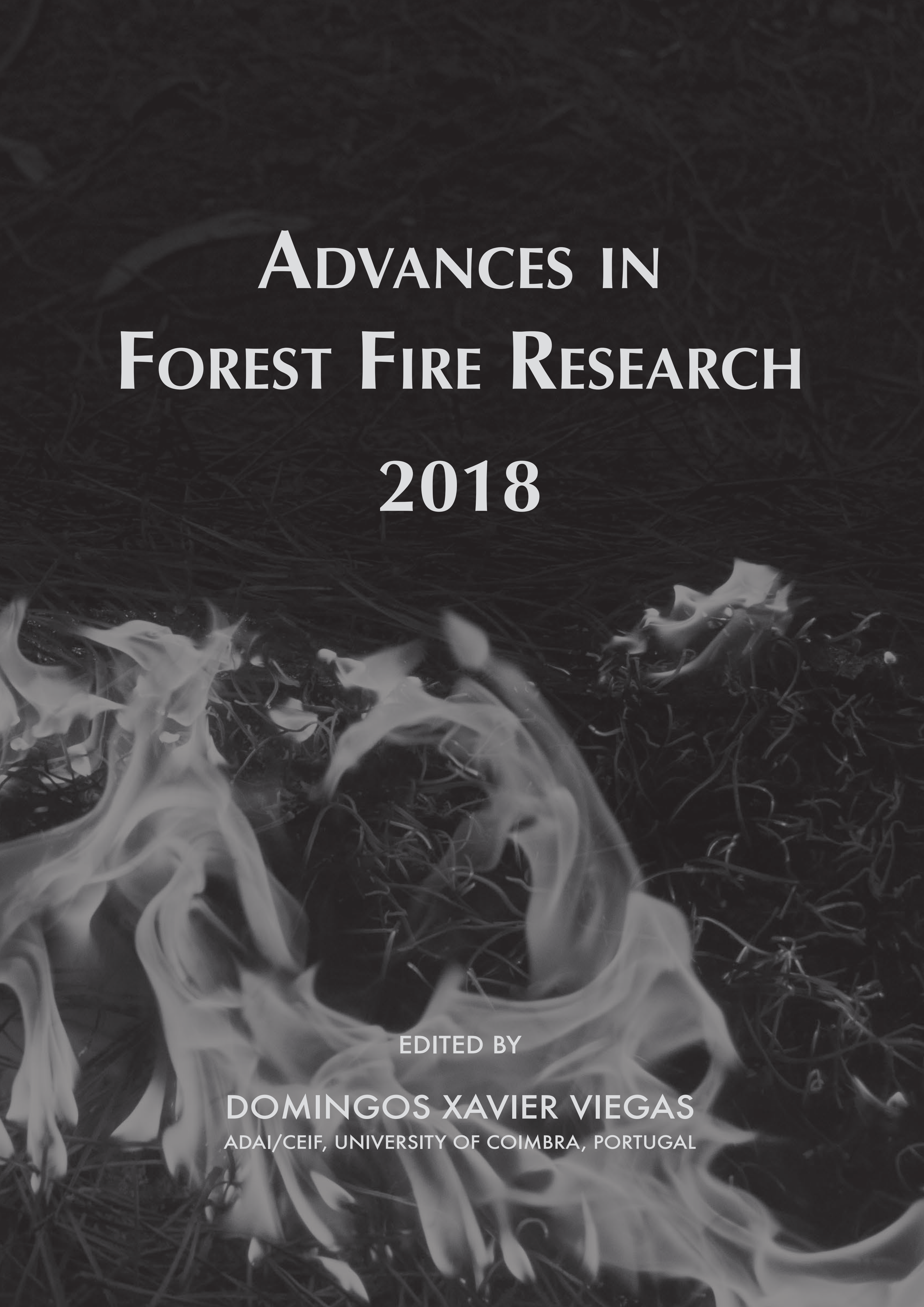

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Short contribution – Fire Management

Numerical simulation of low-intensity fire spread in pine litter

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Abstract

Detailed physics-based models of wildland fire behavior have shown utility as a tool for investigating the physical drivers of fire spread. However, the continued development of such models requires extensive testing against robust experimental measurements. This remains an outstanding challenge for the research community. A particular application space of interest is the simulation of low-intensity fires, in either still-air or backing fire conditions, as such models have been tested relatively little for such scenarios. A numerical tool capable of properly representing the relevant physics is valuable for understanding the impact of prescribed fire activities, which are often carried out in these conditions. Therefore, ongoing efforts are being undertaken to assess the ability of a detailed physics-based model to simulate fire spread in pine needle litter in still air. Particular focus is placed on the representation of flow within the fuel bed and its effect on fire behavior. The experimental data necessary for model testing was obtained from bench-scale flame spread experiments on a 1.5 m long table. The outputs included both global observations of fire behavior and point measurements of physical processes within the fuel bed (e.g. flow). Numerical modeling was conducted with a computational fluid dynamics model – the Fire Dynamics Simulator – using a multiphase formulation to represent the vegetation. Modifications were implemented in FDS to improve the representation of vegetation, particularly related to thermal degradation in the char oxidation stage. Maintaining a constant fuel load, fuel bed bulk densities of 11 kg·m-3 and 20 kg·m-3 were tested and compared. Results show that, for the same fuel loading, there is a lower limit to the bulk density, for which the fire will not spread. While this limit will exist in reality, experimental results suggest that the model over-predicts its magnitude. This appears to be linked to the flow within the bed, as the lower bulk density case resulted in more entrainment, and thus greater convective cooling ahead of the fire front. Further, flow measurements within the bed show that the model is not adequately representing the removal of fuel, and thus increased flow, behind the fire front. In order to more directly assess the numerical representation of the fluid dynamics within the fuel bed, a heated wind tunnel has been constructed. Flow and convective heating through various fuel arrangements and compositions are being tested. This is aiding in the evaluation of the limits of these submodels, particularly as they apply to low-intensity fire spread in litter fuels.

Keywords: numerical modeling, flame spread, fuel structure, flow

1. Introduction

Detailed physics-based models of wildland fire behavior have shown utility as a tool for investigating the physical drivers of fire dynamics (e.g. Mell *et al.* 2009; El Houssami 2016). However, the continued development of such models requires extensive testing against robust experimental measurements. This remains an outstanding challenge for the research community.

A particular application space of interest is the simulation of low-intensity fires, in either still-air or backing fire conditions. Detailed physics-based models have been tested relatively little for such scenarios, and the behavior of these fires can prove more difficult to predict than those which are strongly driven by the wind. A numerical tool capable of properly representing the relevant physics is valuable for understanding the impact of prescribed fire activities, which are often carried out in these conditions. Therefore, ongoing efforts are being undertaken to assess the ability of a detailed physics-based model to simulate fire spread in pine needle litter in still air. Particular focus is placed on the representation of flow within the fuel bed and its effect on fire behavior.

2. Methods

2.1. Experimental methods

Experimental data pertaining to flame spread in pine litter was collected under the calorimetry hood at the University of Edinburgh. Beds of pine needles were re-constructed on a 1.5 m long table with a vermiculite insulation board substrate. This table was instrumented with a series of thermocouples and pressure probes in order to help characterize the mechanisms contributing to flame spread.

The pine needles used were a hybrid cross of pitch pine (Pinus rigida) and loblolly pine (Pinus taeda). These dead needles had a typical moisture content of ~10% at the time of testing. The work presented here focuses on two experimental configurations with an identical fuel load of 0.8 $kg \cdot m^{-2}$. In the first scenario the fuel bed had a height of 0.04 m and a bulk density of 20 $kg \cdot m^{-3}$. The second scenario had a bed height of 0.07 m and a bulk density of 11 $kg \cdot m^{-3}$.

2.2. Numerical methods

Three-dimensional simulations of flame spread in pine litter were carried out using the National Institute of Standards and Technology Fire Dynamics Simulator (FDS), version 6.6.0 (McGrattan et al. 2018). Some new modifications were implemented in the source code, specifically for this work, in order to permit the representation of vegetation through the multiphase formulation (Grishin 1997). In this approach, vegetative fuel is represented as a collection of thermally-thin subgrid-scale particles, which can be described by a set of bulk properties. The multiphase formulation has previously been implemented within an FDS-based framework, known as WFDS (Mell et al. 2009). However, this updated framework is of interest as it represents a re-integration of the vegetation models into the most current version of FDS, where they can leverage ongoing development efforts on other aspects of the code.

Aerodynamic drag within the fuel bed was represented using a Reynolds-dependent coefficient for a cylinder in cross-flow, and convective heat transfer was modeled using the maximum of a natural and forced convective coefficient for a cylinder (McGrattan et al. 2018). Radiative heat transfer was modeled using an extinction coefficient for bulk vegetation. Thermal degradation of the fuel was simulated using Arrhenius reaction models for vaporization of moisture, pyrolysis, and char oxidation (El Houssami 2016). Numerical formulations which were not specific to vegetation, for example the combustion model and radiation transport algorithm followed the default FDS configuration (McGrattan et al. 2018).

A numerical grid resolution of 1.25 cm was used, with the computational domain divided over 48 processors. The ratio of computational time to simulation time was approximately 600:1. In this instance, simulations were terminated after 180 s of simulation time.

3. Results and discussion

An example of the computational domain with a simulated flame front is shown in Figure 1, along with the predicted mass loss for the two different bed configurations. The higher bulk density scenario reaches a quasi-steady burning rate of ~2.0 $g \cdot s^{-1}$. The simulated spread rate was estimated to be 0.43 $cm \cdot s^{-1}$, compared to 0.22 $cm \cdot s^{-1}$ in the experiment. The lower bulk density case briefly attains a similar burning rate but then begins to decay, and the fire is extinguished after 35 s. This is contrary to the experiments, where the flames spread to the end of the table at a rate of 0.29 $cm \cdot s^{-1}$.

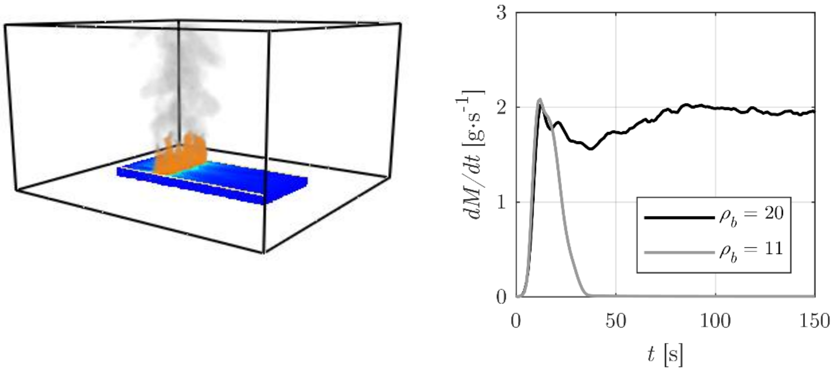

Figure 1 - (left) Example flame spread simulation for bulk density of 11 kg·m3, and (right) simulated mass loss rate for the two different fuel bed bulk densities, ρb.

In order to explore this further, the entrainment flow velocity (parallel to the direction of fire spread) and the convective heat transfer coefficient are shown in Figure 2. These values were obtained within the fuel bed, at a location 0.5 m from the ignition line and 0.025 m from the table surface. The flame front passage is immediately clear in the high density case, marked by the reversal of the flow direction (as entrainment is opposed to the direction of spread ahead of the flame front, and concurrent behind it). The entrainment flow reaches a peak of ~0.2 m·s^{-1} in both directions. In the experiment, the velocity peaks at 0.16 m·s^{-1} ahead of the fire, and 0.36 m·s^{-1} behind it. The model does not capture any increase behind the front, likely because it under-predicts the extent of complete fuel particle consumption following char oxidation, and the subsequent increase in porosity. In the low density case, the fire does not reach the location of interest. However, both the flow magnitude and convective coefficient are greater in the early stages of spread for this configuration. This is a result of the higher porosity, and increases convective cooling ahead of the front, which may help to explain the extinction of the fire.

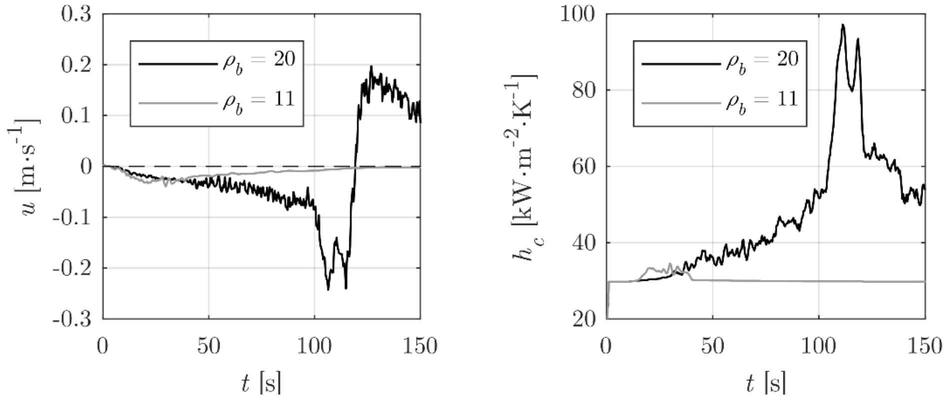

Figure 2 - (left) Entrainment flow velocity, u, and (right) convective heat transfer coefficient, h_c. Values are obtained within the fuel bed, 0.5 m from the ignition line.

4. Summary and ongoing work

Results from numerical simulations of low-intensity flame spread in pine litter, using the multiphase formulation, indicate that, for the same fuel loading, there is a lower limit to the bulk density, for which the fire will not spread. This will also occur experimentally, however data for the relevant values show that the model over-predicts the magnitude of this limit. The 11 kg·m^{-3} fuel bed should still support fire spread.

These results demonstrate a clear dependence of the model on bed structure which is not fully representative of experimental data. Therefore, it is desirable to directly assess the quality of both the drag and convective heat transfer models, as applied to simulations of pine litter beds. To that end, a heated wind tunnel is being used to quantify convection through various fuel arrangements and compositions, particularly those representative of pine litter beds. These results will allow evaluation of limits of these submodels.

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