Numerical simulations of fire spread in a *Pinus pinaster* needles fuel bed

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Abstract. The main aim of this paper is to extend the cases of WFDS model validation by comparing its predictions to literature data on a ground fire spreading in a *Pinus pinaster* needles fuel bed. This comparison is based on the experimental results of Mendes-Lopes and co-workers. This study is performed using the same domain as in the experiments (3.0m×1.2m×0.9m) with a mesh of 49,280 cells. We investigate the influence of wind (varied between 0 and 2 m/s) and moisture content (10 and 18%) on the rate of spread. The WFDS rate of spread is determined using a cross-correlation function of ground temperature profiles. The simulated rate of spread, as well as temperature, compared favourably to experimental values and show the WFDS model capacity to predict ground fires in *Pinus Pinaster* fuel beds.

1. Introduction

Wildland fire is an essential element of ecosystem management and functional ecosystems but causes important damages every year, in terms of economical and ecological issues as well as in terms of human lives. During the summer 2011, spectacular forest fires in Texas state (USA) have killed 4 persons, burnt nearly 14,000 ha and damaged or destroyed over a thousand homes. Because fires fighting tactics can be guided by fire behaviour and propagation, the development and the validation of fire models is a key element for decisional structure. Based on these models, computer systems able to simulate temporal and spatial evolution of a fire can also be used for prevention and training of firefighters in order to better understand behaviour and growth of fire.

Existing forest fire models are of different nature and can be shared into four groups. The first class of models is cellular automata [1,2] where the state of each cell depends on their neighbourhoods by probabilistic rules. The second type of models is the geometric models where the fire front is seen as a line on a two-dimensional surface and its growth is calculated by the envelope method [3,4]. The third group of models is the empirical ones and they are widely used as operational tools [5,6]. These models are based on some physical considerations and empirical coefficients. Last but not least, the fourth group is physical one and is based on a complete physical modelling [7,8]. Among them, WFDS (Wildland urban interface Fire Dynamics Simulator) is a three-dimensional two-phase transport model that uses LES approximations to governing equations of mass, chemical species, momentum and energy. Compared to three physical models, it has been shown in the recent paper of Morvan [8] that the WFDS code is one of the most advanced tools to study wildland-urban interface
fires. However, the validation of WFDS is ongoing but far from complete. Nevertheless, only two validation cases are published in the literature. The first one compares grassland fires simulations and Australian experiments [9]. The second case of validation compares numerical simulations to experimental data of burning individual Douglas fir trees [10].

The aim of this paper is to extend the validation of WFDS by comparing this model to Pinus pinaster needles fires experiments of Mendes-Lopes et al. [11]. The next section is devoted to the presentation of the physical and numerical modelling. The governing equations and models as well as the computational domain and the grid sensitivity are detailed in this section. The third section is dedicated to the results and discussions where the computed values of rates of spread for different wind speeds and moisture contents are compared to experimental data. A comparison of temperature profiles will also be performed.

2. Physical and numerical modelling

2.1. Numerical modelling approach

An overview of the modeling approach is given here; details can be found in Mell et al. [10]. The suite of models, called WFDS for Wildland-urban interface Fire Dynamics Simulator, is developed through a collaborative effort between the U.S. Forest Service and the National Institute of Standards and Technology (NIST) also in the U.S. WFDS is an extension of the capabilities of the FDS5 (Fire Dynamics Simulator version 5.5) to outdoor fire spread and smoke transport problems that include vegetative and structural fuels and complex terrain. FDS is a structure fire behavior model developed by NIST in cooperation with VTT Technical Research Center of Finland, industry, and academics. The methods of computational fluid dynamics (CFD) are used to solve the three-dimensional (or two-dimensional) time-dependent equations governing fluid motion, combustion, and heat transfer.

The numerical model is based on the large-eddy simulation (LES) approach and provides a time-dependent, coarse-grained numerical solution to the governing transport equations for mass, momentum, and energy. The effect of thermal expansion due to chemical reaction and heat and mass transfer enters the computation through an elliptic constraint, derived using the energy equation, on the velocity field. The local mean temperature is then obtained via the ideal gas equation of state. Dissipation of kinetic energy is achieved through a simple closure for the turbulent stress: the constant coefficient Smagorinsky model. The turbulent transport of heat and mass is accounted for by use of constant turbulent Prandtl and Schmidt numbers, respectively. The subgrid heterogeneity of species concentrations and temperature is treated in conjunction with the reaction, heat transfer, and radiation intensity models. Where these effects are important they are included using empirical correlations. The advective form of the continuity equation is solved together with the Stokes form of the momentum equations on a structured Cartesian staggered grid. The spatial discretizations are second-order accurate for uniform grids. Species mass equations are advanced using a modified version of MacCormack’s predictor-corrector scheme and the momentum equations are advanced using a two-stage projection scheme based on the explicit modified Euler method.

Combustion heat release rate is modeled based on the Eddy Dissipation Concept (EDC) model of Magnussen [12]. The solid phase model is similar to models used by previous researchers. In particular, Albini [13,14] presented similar model equations for two-dimensional heat transfer in a medium containing vegetation and air under an assumed heat flux due to an idealize fire shape. Albini’s approach provided a fire spread rate but did not model the pyrolysis or char oxidation of the solid fuel. More recently, similar models for the heat transfer within the vegetative fuel bed have been incorporated in CFD models, which include (to differing levels of approximations) thermal degradation (pyrolysis and char oxidation) and gas-phase combustion, to obtain a more complete approach to predicting the transient behavior of the fire and its buoyant plume (for example [9,15,16]). A review of these methods is given in Mell et al. [10].

Thermally-thin vegetation is assumed to be composed of fixed, optically black, fuel elements. More than one type of thermally thin element (e.g., foliage and thermally thin roundwood) can be
represented. Note that an emissivity of 0.9 is characteristic of wildland vegetation [18] so the assumption that a fuel element is a perfect absorber is reasonable. The thermally thin assumption is commonly used in fire spread models involving fine wildland fuels (grass and foliage of shrubs and trees). The thermally thin *Pinus pinaster* modelled in this study is sufficiently small in size (e.g., $O(1)$mm in diameter) that it is not resolved on the computational grids employed ($O(1)$cm). In the approach used here the thermal, radiative, and drag processes are determined from the bulk vegetative properties (e.g., bulk density). This is similar to other modeling approaches [15,17-19].

Both convective and radiative heat transfer between the gas phase and the vegetation is accounted for, as is the drag of the vegetation on the airflow. In general, as the temperature of a vegetative fuel increases, first moisture is removed, followed by pyrolysis (the generation of fuel vapors), and then char oxidation (also known as smoldering combustion). In the modeling approach used here, the temperature equation for the fuel bed is solved assuming a two stage endothermic decomposition process of water evaporation followed by solid fuel pyrolysis. Char oxidation is not modeled in the version of the model used here.

2.2. **Computational domain and conditions**

The computational domain considered for this study reproduces the low speed wind tunnel of Instituto Superior Técnico (Portugal) and in details the bed presented by Mendes-Lopes et al. [11]. A 2.00 m × 0.70 m bed within a 3.00 m × 1.20 m × 0.90 m domain was used with different values of wind (0, 1 and 2 m/s) and fuel moisture content (10 and 18%). Figure 1 shows an overview of this domain and the fuel bed. It is displayed by SmokeView visualization package [20,21].

![Figure 1. Overview of the computational domain.](image)

Ignition is not well described in the experimental work [11]; it is not specified what alcohol amount and torch power used to ignite the fuel bed. Consequently, in our simulations, the ignition source placed at inlet of the wind tunnel side is insured by a fixed value of heat release rate per unit area (HRRPUA) released during few seconds. This method seems to be a realistic estimate to the experimental procedure. About boundary conditions, top is open, like two faces. The others, along the length, are tempered glass and wall. Considering that there is no loss of heat toward outside, those external walls are assumed to be adiabatic. Five thermocouples (TC1, TC2, TC3, TC4 and TC5) detect flame temperature; they are placed vertically at 0, 125, 250, 375 and 500 mm. Other nine thermocouples are equidistributed horizontally along the fuel bed to estimate Rate of Spread (ROS). In order to take into account only the steady propagation zone for the ROS calculation, the first thermocouple and the last one are not considered. For all simulations, the studied fuel is *Pinus pinaster* needles and its properties used in WFDS are given in table 1.
Table 1. Fuel data used in WFDS simulations

| Moisture content (%) | Height (m) | Load (kg.m\(^{-2}\)) | Density (kg.m\(^{-3}\)) | Bulk density (kg.m\(^{-3}\)) | Surface to Volume ratio (m\(^{-1}\)) |
|----------------------|-----------|---------------------|------------------------|-----------------------------|-----------------------------------|
| 10 or 18             | 0.04      | 0.5                 | 640                    | 12.5                        | 3500                              |

2.3. Rate of spread (ROS) determination and grid sensitivity

As mentioned above, nine thermocouples are placed horizontally along the fuel bed at the litter centre line in order to track flame spread. The rate of spread is determined by a least-squares regression based on thermocouple positions and transit times \( t_i \). These times can be written as:

\[
t_i = t_1 + \sum_{j=1}^{i-1} t_{j,j+1} \quad \forall i \geq 2, j \in [2, \ldots, 7]
\]  

where \( t_1 \) is the transit time to the first thermocouple considered in ROS calculation and \( t_{j,j+1} \) is the time necessary for fire to spread between two successive thermocouples \( j \) and \( j+1 \) which is provided by the abscissa of the resemblance peak:

\[
t_{j,j+1} = \arg \max_{\tau \in \mathbb{R}^+} \left[ C_{j,j+1}(\tau) \right]
\]  

where \( \arg \max \) means that \( t_{j,j+1} \) is obtained such that:

\[
C_{j,j+1}(t_{j,j+1}) \geq C_{j,j+1}(\tau), \quad \forall \tau \in \mathbb{R}^+
\]  

with \( C_{j,j+1} \) designates the cross-correlation function below:

\[
C_{j,j+1}(\tau) = \int_{-\infty}^{+\infty} T_j(t) \cdot T_{j+1}(t-\tau) \, dt
\]

In this relation \( T_j \) and \( T_{j+1} \) are the temperatures measured by thermocouples \( j \) and \( j+1 \). The proposed method to calculate the rate of spread is a continuous method, unlike temperature peaks method [22] which is a discrete one [23]. Indeed, in cross-correlation method, all temperature signals \( T_j \) and \( T_{j+1} \) are considered and not only their peaks. This first method appears to be more precise than the discrete one because it cannot suffer from the temperature peaks determination; that is not easy due to noise due to the flame oscillations caused by the surrounding turbulent flow.

Grid resolution is one of the most crucial parameters in numerical simulations. In this work, numerous tests are carried out up to determinate an optimum grid size. It is selected through a grid cell sensitivity analysis in which influence on ROS is studied. Table 2 contains dimensions of cell, CPU time and result of comparison between the simulated ROS and experimental one for case no wind, moisture content 10%. The simulations are performed using an Intel(R) Core(TM)2 Duo CPU 3.33 GHz with 8 GB RAM computer.

Table 2. Results of grid cell sensitivity.

| Number of cells | CPU time (min) | Relative gap between ROS (%) |
|-----------------|----------------|-------------------------------|
| 19,200          | 13.50          | 24.6                          |
| 26,496          | 34.10          | 10.1                          |
| 36,000          | 51.40          | 8.6                           |
| 49,280          | 80.24          | 4.1                           |

The dimensions of the cell used in this study are 3.4 cm \( \times \) 4.3 cm \( \times \) 4.5 cm, giving a total meshes number of 49,280. Inside the fuel bed, vertical grid cells are half this size. Figure 2 presents an illustration of the grid in horizontal and vertical planes.
3. Results and discussion

As indicated in the introduction, the aim of this work is to propose a new case of validation of WFDS by comparing simulated and experimental rates of spread. Three wind speeds (0, 1 and 2 m/s) and two moisture contents (10 and 18%) are selected for simulations. Six sets of experimental data from Mendes-Lopes et al. [11] are used for the validation of the predicted ROS.

Figure 3 exhibits fire propagation in simulations for each wind speed for moisture content of 10%. It is composed of sequential snapshots of fire for 0, 1 and 2 m/s wind speed values. One can also notice that the rate of spread is increasing when wind speed is rising [1,3,24]. Effectively, wind inclines flame leading to an increase of fuel temperature, pyrolysis reaction and then rate of spread.

Figure 4 compares rates of spread predicted by WFDS code to experimental data of Mendes-Lopes et al. [11] as well as to computed values of Ferragut et al. [25] obtained by means of a two-dimensional surface model for different wind speeds for a fuel moisture content of 10%. This figure confirms and quantifies the augmentation of ROS when wind speed increases and shows a good agreement between our values and the literature ones. Similar tendency has been observed by Boboulos and Purvis [26] using the same fuel with a higher load (about 2.4 kg/m²). Agueda et al. [27] have also observed this trend using straw as fuel with a load close to our value and showed values of rate of spread twice our predicted values. The WFDS rate of spread increases by 74% when wind
passes from 0 to 1 m/s and by 51% when it passes from 1 to 2 m/s. This variation in the slope of the ROS as a function of wind corresponds to the transition from a buoyancy-dominated to a wind-dominated regime [28].

![Wind influence on rate of spread for a fuel moisture content of 10%](image)

**Figure 4.** Wind influence on rate of spread for a fuel moisture content of 10%.

Concerning fuel moisture content, table 3 presents the WFDS predicted values and the experimental data of Mendes-Lopes et al. [11] for a moisture content of 18%. This table shows the same behaviour than the one observed in figure 4 under the influence of wind with relative gaps which do not exceed 4%. Let us notice that the no-wind propagation case cannot be reproduced by the actual version of WFDS code.

| Wind speed (m/s) | WFDS predicted ROS (cm/s) | ROS of Mendes-Lopes et al. [11] (cm/s) | Relative gap (%) |
|-----------------|---------------------------|--------------------------------------|-----------------|
| 0               | --                        | 0.243                                | --              |
| 1               | 0.542                     | 0.536                                | 1.1             |
| 2               | 1.05                      | 1.09                                 | 3.7             |

Table 3. Wind effect on predicted rates of spread for a moisture content of 18%.

After studying the wind effect, it becomes interesting to examine the moisture content influence by comparing the results of figure 4 to the ones of table 3. One can observe a rate of spread decrease when fuel moisture content is rising. An augmentation of 8% of fuel moisture content induces a fall of ROS of 45.1 and 48.4% for respectively wind speeds of 1 and 2 m/s. Indeed, a moisture augmentation means more water in fuel leading to a longer drying step inducing a delayed pyrolysis step and consequently a decrease of rate of spread [27,29].

All WFDS predicted rates of spread for different wind speeds and fuel moisture as well as those computed by a convection–reaction–diffusion model [25], are compared to the measured values of Mendes-Lopes and co-workers. Those data are given in figure 4 and table 3. One can clearly notice a good agreement between our simulated ROS and the measured and computed ones of the literature.

Rates of spread comparison been done, confrontation of the temperature profiles will be performed. Figures 5 and 6 illustrate this comparison between the WFDS predicted temperatures and those of Mendes-Lopes and co-workers. We can see from these figures that WFDS reproduce correctly the measured temperature profiles with a slight difference in prediction of the thermocouple TC1.
4. Conclusion

The present paper deals with the extension of the validation of WFDS by comparing the predicted results to those found in literature for a fire spread in a needles fuel bed. The influence of the wind speed as well as the moisture content has been investigated. The simulation results are in good agreement with the experimental ones of Mendes-Lopes and co-workers and with the computed ones of Ferragut and co-workers.

Although WFDS has been designed to wildland-urban interface fires, we have shown in this study that it can be used to predict ground fires. To the authors’ knowledge, this is the first attempt to check the model ability for this type of vegetation fire.

In a next step of the work, we will investigate the influence of slope and vegetation natures on the fire spread and consider comparison based on other parameters such as heat fluxes or fire front positions. Once fully validated, the WFDS model will be integrated in a decision making support platform to fight wildland-urban interface fires.

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