EFFECTS OF WIND AND TERRAIN SLOPE ON FLAMES PROPAGATION IN A VEGETATIVE FUEL BED

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Abstract
In this work the way the wind and terrain inclination affect the fire propagation across a homogeneous fuel bed was investigated. The role played by these two parameters in fire behaviour was studied, showing that wind velocity affects the rate of spread more strongly than the terrain slope. The evolution of a fire front from a linear ignition source was analysed along with the time evolution of the fire front according to the external condition. The role played by the terrain slope and atmospheric wind in determining the rate of spread was quantified, showing how the latter parameter has a stronger dependency on the rate of fire spreading.

1. Introduction

Wind and topographic slope are commonly considered to be the main factors determining wildfires propagation [1]. Wind has the effect of tilting the flame forward, increasing convection and radiation transfer of energy to the unburnt fuel, inducing faster rate of spreads. Slope effect is often described as being similar, because it tends to make the ground and the fuel closer [2]. Consequently, most wildfire behaviour models and fire behaviour prediction systems take account of the wind and slope effects when computing the rate of spread [2, 3, 5].
In order to analyze the complexity of the fire phenomena according to a numerical point of view aiming to provide information about the behaviour of fire spreading, semi-empirical and empirical approaches were considered. However, due to their intrinsic limits to correctly quantify the fire propagation rate, since the late 1990, a physically-based approach has been followed to develop two-phase flow transport models that explicitly take into account the interaction between the gaseous phase and the fuel to model accurately the convective heat transfer [6, 7]. Among physically-based models, WFDS is a three-dimensional two-phase transport model that solves the conservation equations for mass, momentum, energy and chemical species. Because of these attributes, this model can be a valuable tool for the investigation of the slope effects under various conditions of wind and terrain inclinations. This issue was accomplished by comparing the results of the model simulations with some findings from experimental tests available in the literature.

2. Mathematical model

To perform the simulations presented in this work the WFDS software was used: it is a free physics-based code developed by NIST (National Institute of Standard and Technology) as an extension of an already existing software for the simulation of fire propagation in enclosures (FDS). The main references for this code are from Hinze [8], McGrattan *et al*. [9] and Cox [10]. More details about the code, from the same authors of this paper, are provided elsewhere [11, 12, 13].

3. Mesh sensitivity

The different phenomena involved in forest fire modelling cover an extremely variety of length and time scales, making almost impossible the definition of a single set of scaling parameters. In order to attaint such a issue, the definition of a length (D) to scale the characteristic flame diameter derived from the Zukoski's analysis [14] was adopted. The mesh resolution was set by the dimensionless ratio D/δ [15]: the quantity D/δ_x can be considered as the number of computational cells spanning the characteristic diameter of the fire; values for D/δ_x, useful to get a good resolution of the calculation, ranges from 4 to 16. In our simulations a value of about 16 of such a ratio was chosen implying, a maximum mesh size of 0.27 m.

4. Flat and sloped terrain simulations

To study the fire propagation rate on flat and sloped surfaces, a grassland domain was considered. The surfaces used in the simulations were 30 m long (x) and 40 m wide (y). The physical characteristics of the grass adopted in the simulations are those based on NIST experiments on Australian grass [16]. Grass was ignited along a 1 meter wide line located in correspondence of the beginning of the grass and having length equal to the domain size. The maximum heat flux release rate associated to the ignition source was set to 500 kW/m^2. In order to investigate the influence of the terrain slope, three different runs with sloped domains of 0°, 15° and 30° were simulated. In all the cases, however, the fire was ignited on a flat surface, 3 meters before the beginning of the inclination of the terrain. In all the modelled conditions, in order to save computational time, a symmetry plane was considered (represented by blue planes in Figures 1 and 2). Simulations were run with different wind velocity, i.e. 0, 2, 3, 4 and 5 m/s.

The results reported in Figure 1 (no wind) show that the trajectory of the flame was almost vertical for both flat and inclined terrains; the gas flow in the vicinity of the fire front is mainly affected by the expansion of the hot gases above the combustion zone and this buoyancy flow (plume dominated fires) induces the entrance of fresh air from both side of the fire. The presence of a sloped surface induces an increase in the flame front propagation rate: all the domain burns in about 39 s and 32 s for the 15° and 30° inclinations, respectively, while it takes about 60 s in the case of the flat surface. With respect to the results presented in Figure 1, those in Figure 2 highlight the action of the wind on the fire propagation characteristics: in this case the fresh gas inflow deviates significantly the trajectory of the flames inducing the ignition of the solid fuel located far ahead the fire front. This effect is also visible in some snapshots of the Figure 2 where the grass combustion fronts span a far larger surface with respect to the case without wind.

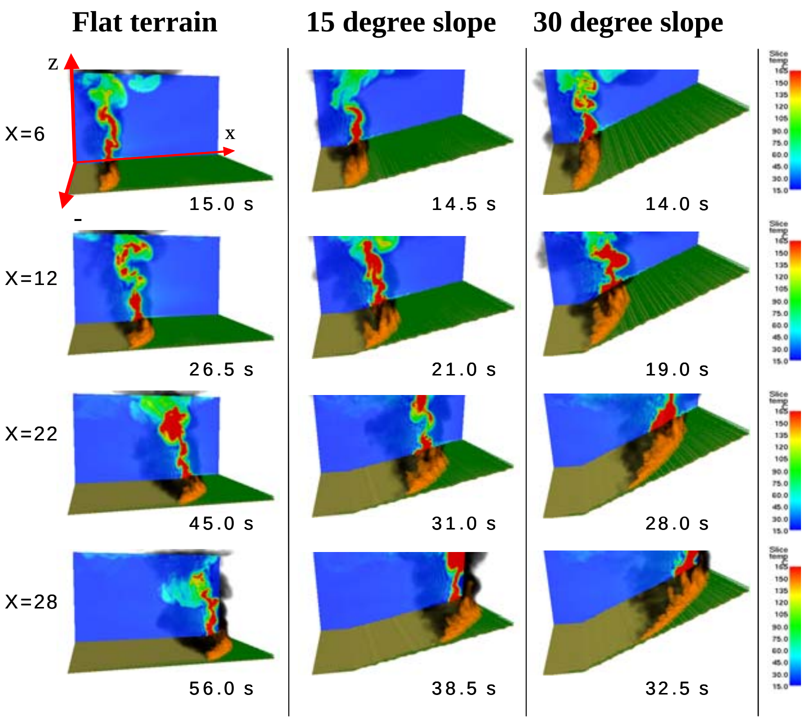

Figure 1. Example Fire spreading on flat and slope terrains in the absence of wind. Picture on the top on the left includes the axis orientation. The sequence of pictures show the reaching of the same x position at different times.

Under strong wind conditions (Fig. 2), the shape of the fire is markedly deviated from the vertical (wind driven fires), inducing a shearing and a tilting of the flame at the top of the fuel layer. The action of the wind on the fire dynamics is also shown by the formation of fingers of flame impinging alternatively on the fuel surface (top and central snapshots in Figure 2).
In order to evaluate the rate of spread (ROS) of the flames propagation, the shape of the fire fronts was directly deduced from the distribution of net heat flux profiles (kW/m^2) produced by the grass combustion: the contours of the fire front was defined and the areas spanned by the fire in every modelled condition evaluated.
The simultaneous influence of wind and terrain slope over the rate of spread is shown in Figure 3, where the ROS vs. the slope (ROS_S) at fixed velocities (Fig. 4A) and ROS vs. wind velocity (ROS_V) at fixed plane slopes (Fig. 4B) are displayed. Figure 3 shows clearly how the rate of spread increases at increasing

both slope and wind velocity since both make the distance between flames and fuel shorter, even though the effect of wind velocity resulted more marked.
According to literature [3, 17, 18], the dependency of ROS on wind velocity and slope can be expressed as a sum of this two contributions. For our simulations, results were fitted ($r^2 = 0.9586$) by the following expression:

$$R_l = a + b * v^{1.36} + c * \alpha^{0.8} \tag{1}$$

where a is the reference spreading rate at $v = \alpha = 0$, v is the wind velocity and α is the inclination of the domain. The parameters a, b and c in the Equation (1) were equal to 12.996, 5.607 and 2.570, respectively.

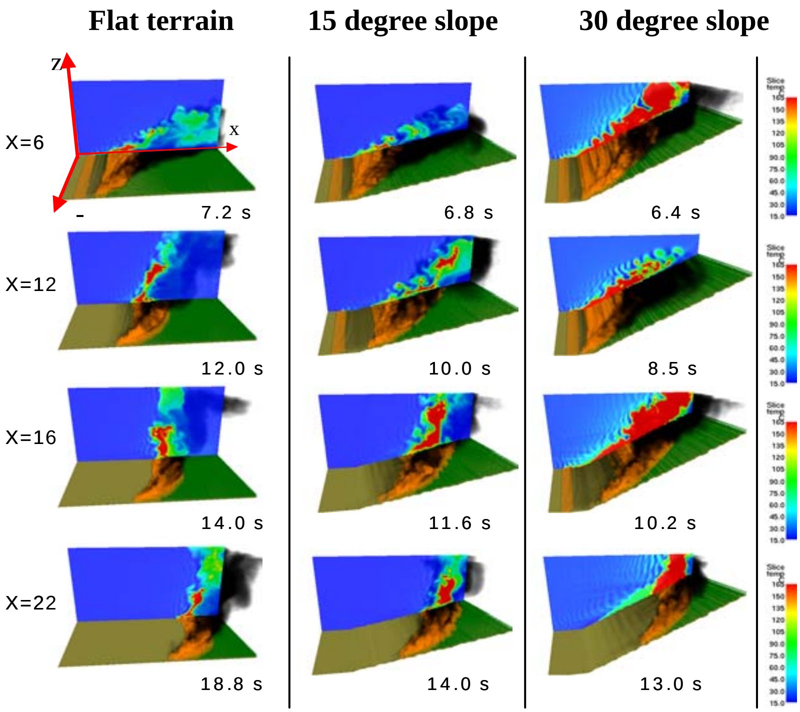

Figure 2. Fire spreading on flat and slope terrains for wind blowing at 5 m/s. Picture on the top on the left includes the axis orientation. The sequence of pictures show the reaching of the same x position at different times

Equation 1 shows an almost linear dependency of ROS on α (fig. 4A) and power-law contribution with respect to the wind velocity (fig 4B). The non linear dependency of ROS_W with respect to the wind velocity is also confirmed in literature [17] by Boboulos and Purvis. The authors, performing laboratory tests for studying the fire propagation across beds of *Pinus halepensis* and *Pinus pinaster* pine needles, proved a more than linear trend of ROS respect to the wind when different plane inclinations were considered.

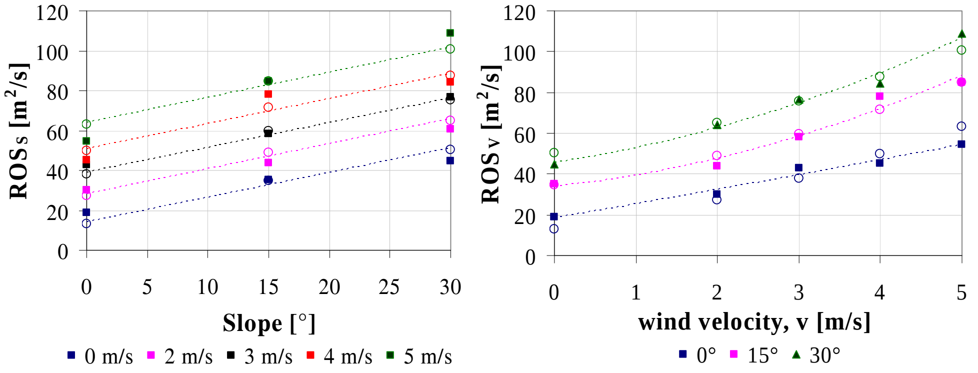

Figure 4. A) ROS_S [m^2/s] vs. slope [°] at fixed wind velocities. B) ROS_V [m^2/s] vs. wind velocity [m/s] at fixed slopes. Full square symbols stand for modelled values simulated in the different conditions. Dashed lines display the ROS values according to equation 1: circles represent the corresponding ROS values calculated by the fitting equation

5. Conclusions

The results proposed in this work showed that the use the physically-based model WFDS- specifically designed to simulate the fire behaviour - can be an effective tool to correctly study the way flames spread across flat and sloped domains. Results confirm the strong dependency of the rate of fire spreading on wind velocity and terrain slope: the role of these two parameters was expressed through an easy relationship where the contribution of these two parameters was clearly represented: the ROS resulted to have a power-law dependency on wind velocity, while the slope of the domain affects almost linearly the ROS. The results obtained provide a basis in order to carry out a risk analysis for fire spreading in vegetation species taking into account specific terrain features and climate characteristics in a specific geographic area.

References

[1] Byram G.M., "Forest fire behaviour", in '*Forest Fire: Control and Use*'. McGraw-Hill: New York Ed. KP Davis

[2] Sharples J.J., "Review of formal methodologies for wind-slope correction of wildfire rate of spread". *International Journal of Wildland Fire* 17, 179-193 (2008)

[3] Rothermel C., "A mathematical model for predicting fire spread in wildland fuels", in: Research Paper INT-115: US Department of Agriculture, Forest

Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 1972, p. 40.

[5] McArthur A.G., Weather and grassland fire behaviour. Department of National Development, Forestry and Timber Bureau, Leaflet No. 107. (Canberra, ACT) (1966)

[6] Morvan D., Dupuy J.L., "Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation", *Combustion and Flame* 138: 199–210 (2004)

[7] Linn R.R., Cunningham P., Numerical simulations of grass fires using a coupled atmosphere-fire model: basic fire behavior and dependence on wind speed. *Journal of Geophysical Research* 110: D13107 (2005)

[8] Hinze J.O.: *Turbulence*. 2nd Edition. McGraw-Hill, 1975.

[9] McGrattan K., Hostikka S., Floyd J., Baum H., Rehm R., Mell W., McDermott R.: "Fire Dynamics Simulator (Version 5) Technical Reference Guide - Volume 1: Mathematical Model". NIST Special Publication 1018-5, (Available at: http://www.fire.nist.gov/fds/), (2010)

[10] Cox, G.: Basic Considerations. In: *Combustion Fundamentals of Fire*. Ed. G. Cox. Academic Press, London, (1995)

[11] Ciambelli P., Malangone L., Russo P., Vaccaro S., Preliminary Study of Wildland Fires, *Processes and technologies for a sustainable energy,* Ischia, June 27-30 (2010)

[12] Ciambelli P., Malangone L., Russo P., Vaccaro S.: Preliminary Modelling Study of Wildland Fires by WFDS, *VI International Conference on Forest Fire Research* D. X. Viegas (Ed.), Coimbra, 15-18 November (2010)

[13] Malangone L, Russo P, Vaccaro S.: The role of the terrain geometry on the flames propagation through a vegetative fuel bed *MCS 7* Chia Laguna, Cagliari, Sardinia, Italy, September 11-15 (2011)

[14] Zukoski E.E.: "Properties of Fire Plumes", Chapter 3, *Combustion fundamentals of Fire*, G. Cox Editor, Academic Press, pp.101-220, 1995

[15] McGrattan K., McDermott R., Hostikka S., Floyd J.: "Fire Dynamics Simulator (Version 5) User's Guide". NIST Special Publication 1019-5,. Available at: http://www.fire.nist.gov/fds/ (2010).

[16] Mell W., Charney J.J., Jenkins M.A., Cheey N.P., Gould J.: "Numerical simulations of grassland fire behavior from the LANL-FIRETEC and NIST-WFDS models". *Proc. EastFIRE Conference*, May 11-13, Fairfax (VA), 10 pp., (2005).

[17] Boboulos, M., Purvis, M.R.I.: "Wind and slope effects on ROS during the fire propagation in East-Mediterranean pine forest litter", *Fire Safety Journal,* 44: 764–769 (2009).

[18] Viegas, Domingos X.: "Slope and wind effect on fire propagation". *Int. J. of Wildland Fires*, 13: 143-156 (2004).

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