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A convective model for laboratory fires with well-ordered vertically-oriented fuel beds

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ABSTRACT

Several studies in the literature explore the connection between rate of spread (ROS) and wind in wildland fires. These studies show very different positions about the role of radiation and convection as heat transfer mechanisms. In the case when the fuel bed is well-ordered and vertically-oriented, there seems to be a consensus leading to suggest that convective heating is the dominant heat transfer mode in that case. The purpose of this work is to propose a convective semi-physical model for the behaviour of the rate of spread in wind, when the fuel bed is vertically-oriented. Due to a specific fuel bed arrangement, flame radiation –i.e. radiation from the part of the flame above the vegetal stratum– is neglected. Only horizontal radiation from the fuel burning particles area and convective heating are taken into account. Convective heat transfer is assumed to be the primary heat transfer mechanism. The proposed model is confronted to 172 laboratory fires with a wide range of fuel characteristics. The predicted results are also compared with two simplified models from the literature. Statistical tools are used to check the agreement between the predicted ROS and the observed one where a strong agreement is generally observed, irrespective of fuel bed characteristics.

1. Introduction

Wind is commonly accepted [1] as one of the major factors that affects a fire is rate of spread. Generally, fire burning aided by wind expresses higher rates of spread than in 'no-wind' cases. Several studies have described the relationship between the ROS R and wind velocity U, where a power function of the wind velocity ($R \propto U^n$) is commonly fitted to ROS data [2,3]. The exponent n derived from these studies, however, is inconsistent. For instance, Thomas and Pickard [4], Wolff et al. [5] and Catchpole et al. [6], observed $n < 1$ whereas the results provided by Rothermel and Anderson [7], Rothermel [8], or Mendes-Lopes et al. [9] suggested $n > 1$. All these cases are part of what Rothermel and Anderson [7] presented as the three possible curve shapes for ROS in wind conditions.

The main heat transfer mechanism induced by fuel bed geometries seems to be important in order to explain those different curve shapes. Indeed, fire spread models commonly assume a steady spread [8,10,11], and the interface between burning and preheating fuel related to fire spread has been widely studied, especially for shallow and continuous fuel beds [8,12,13]. Radiant heat transfer from the flame to the unburnt fuel has been widely considered as the primary mechanism controlling fire spread, the heating and ignition of fuel particles by flame contact being largely neglected [14]. However, Anderson [15], Fang [16] for surface fires, and Van Wagner [17] for crown fires, indicated that the radiant heat transfer could only account for a part of the total heat flux necessary to sustain a spreading fire. Some authors [18,19] also found that radiation heat transfer was not sufficient to ignite fuel bed particles due to the too low fuel particles temperature at the flame's arrival. Note also that some recent results on the wildland fire flame spread and ignition mechanisms detail the location where the local heat flux received by downstream surface in wind-driven fires is maximum [20].

At the field scale, some fuels display discontinuities between individual plants. In order to investigate the fire behaviour in these fuel types, some authors have proceeded to laboratory experiments where fuel beds are made of well-ordered, vertically oriented particles with regular spacing. These fuel beds are usually constituted by matchsticks [12,21,22], toothpicks [5] or laser-cut cardboard [23]. For those discontinuous fuel beds, *i.e.* fuel beds with significant gaps between individual fuel elements, it has been suggested that convective heat transfer is necessary to correctly understand the fire spread mechanisms [2,3,19,24,25]. Finney et al. [14] also conclude that the

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ignition of fuel particles after direct contact is the main mechanism thanks to which the fire propagates.

In a recent work [26], Finney et al. focused on the role of convective and radiative heating on fire spread. Their measurements performed on a set of experiments conducted on those discontinuous fuel beds show that radiation causes a slow increase of the fuel temperature whose value remains below 100 °C. Moreover, when bursts of flame and hot gases contact intermittently the unburnt fuel particles, fuel temperature increases fastly. In this type of fuel bed arrangement, convective heating seems to be the main heat transfer mechanism.

The main purpose of this paper is to present a simplified semi-physical model which is able to correctly reproduce the ROS in wind conditions, when the fuel bed is well-ordered and vertically-oriented. The main phenomena in fire spreading are represented by some physical laws, but nevertheless some empirical laws could be added. By using some approximations, this model tries to solve, the equations governing heat transfer and combustion, and as such can be classified as a simplified semi-physical model. Particularly, these simplifying assumptions avoid into account taking the gas transport equations explicitly, which leads to a model constituted by algebraic equations with two advantages: a computational time close to zero and an explicit analytic relationship giving the ROS as a function of the wind velocity and the main characteristics of the vegetal stratum and the environment. Among the three usual heat transfer modes, flame radiation –the radiation from the part of the flame located above the vegetal stratum– is neglected because it is weakly received by the fuel particles due to their verticality –following the work of Finney et al. [26]. Radiation from the flame base –fuel burning particles area– is obtained thanks to the assumption of an equivalent radiant panel. Because of the weak packing ratio and the well-ordered geometry of the fuel bed, the air flow easily enters the vegetal stratum and a part of this flow is going to go out through the flame base-unburnt fuel bed interface. Then the convective effects with direct flame contact are assumed to be important and represent the main heat transfer mechanism. This assumption is supported by the work of Finney et al. [26]. Obviously, in the case of a continuous fuel bed, radiation cannot be neglected and may often control the flame spread, especially with large fires.

In a first section, the main equations of the model are set. Especially, horizontal and vertical velocities of the gaz flow in the vegetal stratum are estimated, which involves the divided streamline: gases get out of the flame base through its upper part or by the flame base-unburnt fuel interface. An assessment of the contact flame power and its absorbed part for the fuel preheating is done. Finally, according to Balbi et al. [27], a thermal balance on the preheating fuel bed gives the expression of the ROS.

This convective model is composed of three universal model parameters –set up on two experiments– and their value is the same whatever the experiment series.

In a second section, the model is confronted to several sets of laboratory experiments and is compared to two other empirical models found in the literature, namely the simplified models provided by Wolff et al. [5] and Catchpole et al. [6]. The effectiveness of the model is evaluated with usual statistical tools, such as the normalized mean square error (NMSE), the fractional bias (FB), and the Pearson correlation coefficient (r).

2. Main equations of the model

In order to obtain a simplified model, it is necessary to process complex phenomena in a simple way. Particularly, the gases movement in and around the flame is considered to be stochastic, but its effects on the rate of spread are completely deterministic. The proposed model is obtained by considering mean movements in time and space, so equivalent laminar flows are used in the place of turbulent flows and the main physical characteristics of the fire front (temperature, flame height…) are replaced with mean values. The fire front is considered to be a linear one.

2.1. Stream lines

Pyrolysis gases are emitted from the flame base, i.e. the fuel burning particles area –denoted by ABCD in Fig. 1. The temperature in the preheating zone (BB'C'C in Fig. 1), which is close to the one suggested by Pitts [2], ranges from ambient temperature to ignition temperature. The air stream which comes from the burnt area crosses the flame base and mixes with pyrolysis gases is subjected to progressive drag forces and driven to the top of the flame base, due to buoyancy. Due to the low fuel bed density and the vertical arrangement of the fuel particles, the drag forces are weak compared to a continuous fuel bed. So the stream lines will go out through the front panel of the flame base –denoted by BC in Fig. 1– or through the top of the flame base –denoted by AB in Fig. 1. Those two air streams are split by the line denoted by EB in Fig. 1. So, the flame can be divided in two parts, an external part above the vegetal stratum and an internal part which directly contacts the unburnt fuel bed and which will give the major part of energy transfer. The existence of this internal part of the flame has been emphasized by temperature measurements [28] or gas velocity measurements [29] in the fuel bed.

Therefore, the flame contour is determined by the intersection of the flame base with stream lines number 1 and 3 (Fig. 1). The plume is

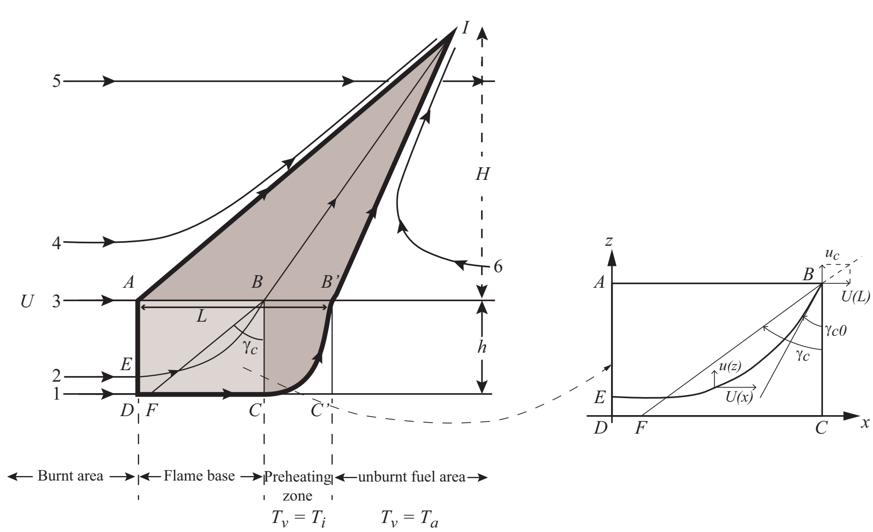

Fig. 1. Flaming zone combustion profile in presence of wind in the normal direction.