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Combustibility of potential embers

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Abstract: Spot fires create serious difficulties to fire suppression tactics, increasing their negative impact in extreme fire danger conditions. In order to predict the maximum spotting distance, the duration of combustion reaction of a given particle should be estimated. In the present article, the results of an experimental laboratory study of the combustibility of *Pinus pinaster* cones and scales and *Eucalyptus Globullus* pieces of bark that can be potential short to long distance embers in forest fires, are reported. Tests were made for values of the orientation angle of the main axis of the particles in relation to the horizontal direction or the incident wind in the range of ±90º and for flow velocities up to 6m/s. Particles were ignited with a flame and mass loss due to flaming or glowing combustion of the particle was continuously registered. Residual mass, duration of the burnout times are reported for each case. Empirical models to estimate the continuous mass loss of the particle in combustion are proposed for the range of test conditions.

Keywords: *forest fires, spot fires, firebrands, combustibility.*

1. INTRODUCTION

Spot fires are one very important mechanism of forest fire spread that can play a decisive role especially in extreme fire danger conditions. It is well known that spot fires can overcome natural barriers and fire breaks creating difficulties to fire suppression tactics. On the other hand short to medium distance spot fires are associated to some fatal accidents given the difficulty in predicting or observing them during actual operations. In spite of their importance spot fires are yet poorly studied due to their intrinsic complexity and the variety of involved processes and factors.

A key issue in the study of spot fire propagation is the analysis of the combustibility of the fire brands or burning particles that can be potential embers and ignite new fires when they land. In order to predict the maximum spotting distance of a given particle it is necessary to estimate the duration of its combustion reaction. In order to assess the probability of a given particle to produce a new fire it is important to know if it is either burning with flame or if it is just glowing. During its flight a particle is immersed in an ambient flow that may have a local velocity changing continuously both in modulus and in direction. These two parameters will certainly affect the combustion regime of the particle and its mass loss rate and there seems to be insufficient data in the literature on this aspect.

Tarifa et. al (1967) performed a pioneer research on the transport and combustion of firebrands analyzing the influence of the particles density, shape and of wind velocity in the lifetime of burning wooden brands. Many other researchers have followed this investigation like Muraszew et al. (1975), who created an empirical model to predict the trajectories of cylindrical firebrands released above a fire whirl, and Albini (1979, 1981, 1982 and 1983) who produced several theoretical models to calculate spot fire distances from several types of firebrand sources. Ellis (2000) extensively studied the aerodynamic and combustion characteristics of pieces of bark from several species of eucalypt. Terminal velocity, flaming and smouldering time data were obtained from the analysis of these firebrands in a vertical wind tunnel experiments. This author proposed a theoretical model to predict the maximum spotting distance in relation to the initial firebrand's characteristics, fire and wind conditions. More recently Sardoy et al. (2007) presented the results of numerical studies on transport and combustion of firebrands from burning trees. These authors put in evidence the role of initial firebrand density and thickness on the type of combustion (flaming or smouldering) when the particle reaches the ground, correlating fire intensity, wind velocity, firebrand thickness and its final density to estimate the time that the firebrands remain burning in the thermal plume.

In the present study we analysed the combustibility of *Pinus pinaster* cones and pieces of bark of *Eucalyptus Globullus* that are known to be potential short to long distance firebrands. A vertical combustion tunnel was used to assess the flaming and glowing combustion of particles fixed at various angles of orientation in relation to vertical flow direction. Results on the duration of combustion for different wind velocities are given. Empirical models to estimate the continuous mass loss of the particles are proposed for the range of test conditions.

2. METHODS

We assume that a firebrand has one main axis that is determined by its largest dimension. In each test the particle is ignited at one of its extremities by a flame. In some cases the combustion front advances mainly along the particle axis either as a flaming or as a smouldering front. In this case we can make a one-dimensional treatment of the problem. In other cases the combustion is generalized to the entire surface of the particle. In this case it is better to analyze the combustibility of the particle as a whole. The angle θ between the axis of the particle and the vertical datum, that is parallel to the local flow velocity, is defined in figure 1. This angle is positive in figure 1 and is negative if the ignition is made at the other end of the particle.

In the general case the flaming combustion phase (FC) has a certain duration t_f and when it is extinguished the reaction continues as glowing or smouldering combustion (SC) until complete consumption of the particle or complete extinction of the chemical reaction (CE) occurs. This is called the burnout time t_b that is a very important parameter to assess the possibility of a given particle having to potentially start a new ignition after landing.

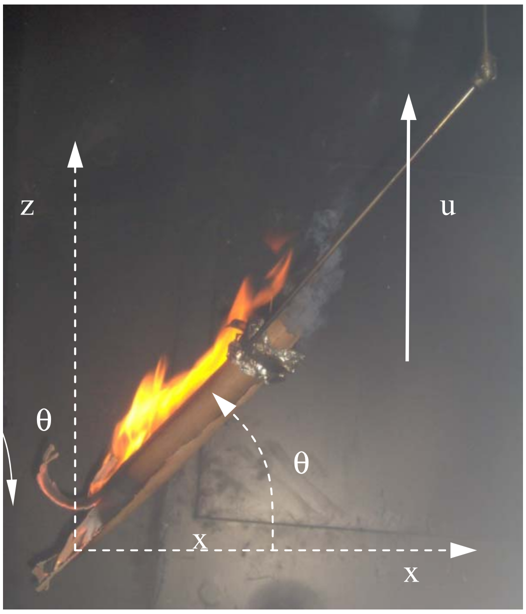

Figure 1. Definition of the orientation angle θ between the particle axis and the horizontal direction. The flow velocity is vertical from the bottom to the top of the picture.

The loss of mass of the particle during its travel from the main fire to the ground is a very important feature of particle combustion. It affects mechanical and aerodynamic properties of the particle and also its potential to start a new ignition. In some cases it may not be possible to distinguish between the different phases of combustion, either because they are not well defined or because there is lack of information on the transition from one phase to another, as it is the case when one is attempting to model *a priori* the mass decay of a given particle. In these cases the overall mass decay of the particle can be treated approximately as a global process using the following descriptive equation:

$$m = m_0 e^{-k_0 t} \tag{1}$$

This equation is valid for the duration of the combustion phase, $t<t_b$ where t_b is the burnout time corresponding to the extinction of smoldering combustion. This time was determined either by direct observation of the particle or by the verification of the lack of mass decay in the mass loss curve.

3. EXPERIMENTAL SETUP

In this study we analyse the combustibility parameters for two different types of potential embers as a function of the local flow velocity and the orientation of the particle in relation to the flow velocity or to gravity direction (in the case of no wind). The particles that were tested are the following: **PC** Pine cones – from *Pinus pinaster* trees; and **EB** Eucalyptus Bark – curled pieces of bark of *Eucalyptus Globullus* trees.

EB are known as very good potential embers due to their good aerodynamic properties and also because they can burn for long periods and produce spot fires at large distances. They have been the subject of other studies namely Ellis (2000). EB particles were ignited at either extremity as it was assumed that they were homogeneous along their main axis. Recording of mass loss was considered to start only after the external ignition source was put out. At this time the mass of the particle was m_i a value normally less than its nominal initial value m_o.

The Vertical Combustion Tunnel (TCV) is a structure that was designed and built on purpose for the study of aero-thermodynamic properties of burning particles that can be considered as potential embers. It is installed at the Forest Fire Research Laboratory of ADAI at Lousã, since 2006. A photo of TCV is shown in figure 2.

The TCV has total height of 6.5m and has a vertical duct with a suction axial fan placed on its top. The air enters through two lateral inlets passes a contraction (1x0.5m^2) and enters the working chamber that has an increasing cross section ending with (1x1m^2). The flow velocity in the tunnel can be varied continuously from zero up to a maximum value of the order of 30 m/s in the contraction section. A platform placed at one of the lateral walls of the TCV supports an electronic balance that is used to evaluate the evolution of the mass of the particle. A specially designed support was used to fix the particles with a predefined angle in relation to the vertical flow in the TCV (figure 1).

Figure 2. The Vertical Combustion Tunnel (TCV) of the Fire Laboratory of ADAI.

4. RESULTS AND DISCUSSION

The duration t_b of the SC for EB particles is shown in figure 3 as a function of orientation angle θ for five different flow velocities. In the no wind tests t_b increased with θ to reach values of the order of 800s and then decreased to values of the order of 400s.

The results obtained in tests with wind are very similar. For θ<0º the value of t_b increases continuously but it decreases for small positive values of θ then t_b increases again for θ <45º. For U>2.2 m/s t_b increases in the range 0º<θ<45º assuming values close to those found for U=0 m/s. For U>5.5 m/s combustion was not sustained in the present conditions.

In tests without wind there are two aspects that justify the variation of t_b with θ. The first aspect is the relative dominance of SC phase in relation to FC. The second aspect is related to the fact that the bark is only partially consumed and does not burn entirely.

For θ <0º the first aspect contribute to increase the value of t_b while the second aspect makes it decrease. When 0º<θ<30º there is SC and the bark is consumed entirely so t_b increases. For θ=45º the burning residue of the bark falls and the SC phase is practically non-existent. For θ=90º the flame surrounds the entire particle and when it is extinguished the particle does not break up and the combustion continues as SC.

The presence of wind introduces some additional factors. As happened for the no-wind cases SC dominates for θ<0º and FC dominates for θ>0º. For θ<0º combustion is made against wind and the reaction extinguishes very quickly leading to values of t_b that are lower than those obtained without wind. This tendency decreases with increasing θ, therefore t_b also increases with θ in this range. For positive values of θ there is a consumption of the particle by the flame but the flow destroys the smouldering residue and therefore this phase is practically non existent in this range for high values of U. For U=2.2 m/s the value of t_b in the range 45º<θ<90º is practically the same as for U=0 m/s. For relatively high values of U the burning residue is destroyed even for θ=90º. This fact associated to the very quick combustion of the particle leads to another decrease of t_b.

The exponential mass loss coefficients k_o for EB are shown in figure 4. The justification of the evolution of k_o follows closely that given for t_b.

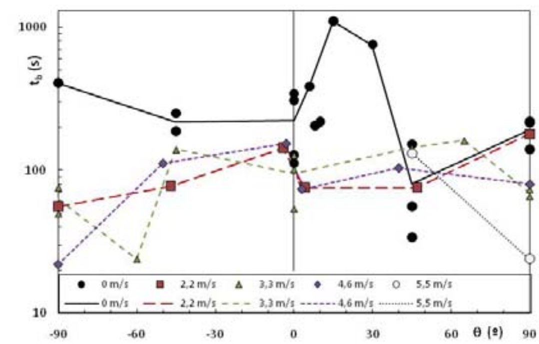

Figure 3. Duration t_b of combustion for EB as a function of orientation angle and flow velocity.

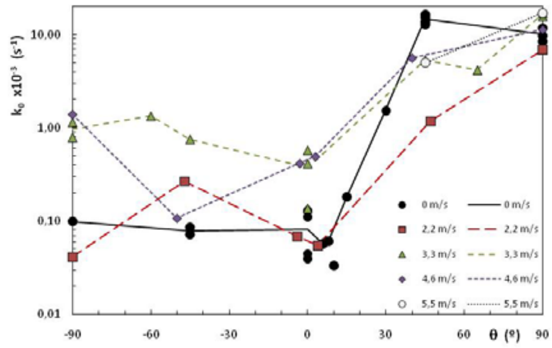

Figure 4. Exponential mass loss coefficient k_o variation during the entire combustion process for EB as a function of orientation angle and flow velocity.

In the range -90º< θ<0º the values of k_o remain practically constant for each value of *U*. Only in the cases of θ=-45º and *U*=2.2 m/s and *U*=4.6 m/s the data points do not follow this trend. For positive values of θ the value of k_o increases. Only for *U*=0 m/s the value of k_o is maximum for θ=45º due to the fact that burning residue falls and all the combustion is made in FC regime as it was explained above. In this range k_o increases with *U*, the sole exception is the case of *U*=0 m/s. For θ=90º practically all the values of k_o are the same exhibiting a very dependence on *U*.

Ellis (2000) tested tethered pieces of *Eucalyptus Bicostata* bark with θ=0º and flow velocities of the order of 5 m/s, and measured rates of mass loss between 0.0011 and 0.0027 g/s that are slightly above ours for 4.6m/s. On the other hand the results obtained by Ellis (2000) for the rate of spread of the combustion reaction are in the range of 0.0047 to 0.0093 cm/s that is below our results for the maximum velocity of 4.6 m/s.

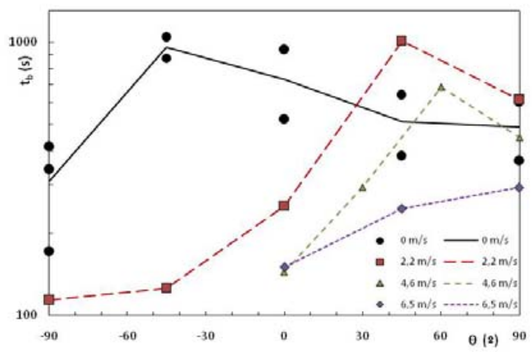

Figure 5. Duration t_b of SC for PC as a function of orientation angle and flow velocity.

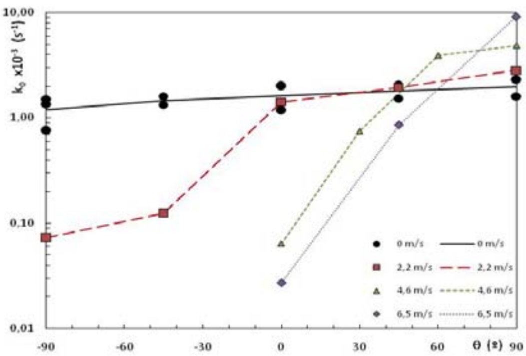

Figure 6. Exponential mass loss coefficient k_o variation during the entire combustion process for PC as a function of orientation angle and flow velocity.

Results of burnout time t_b for PC are shown in figure 5 as a function of θ and flow velocity. For *U*=0 m/s there is an increase of t_b in the range -90º<θ<-45º as the FC extinguishes very rapidly for θ=-45º. For greater values of θ the burnout time is reduced continuously. For tests with wind t_b increases with θ as the mass of the PC that is consumed is greater; for θ<0º only the upper part of the PC is burned. In the range 45º< θ<90º the PC is burned completely; for θ=90º the flame engulfs the PC and it burns relatively quickly.

The results presented in figure 6 for the variation of k_o for PC show that this parameter increases continuously with θ in all situations. It is interesting to notice that for θ<45º the value of k_o decreases with increasing flow velocity while the contrary happens for θ>45º.

5. EMPIRICAL MODEL

We propose an empirical model to predict the mass loss of the particle during flight. The determination of the fitting model, $z_i=f_i(\theta,u)$ for k_0 and t_2 of **EB** and **PC** experimental data was a result of 2D and 3D consecutive data analysis.

In the 2D data analysis the case of u=0 and θ variable has been considered. With this analysis, we intended to identify the functional relations between variables k_0, t_2 and variable θ, supposing that once established these functional relations might be useful as a starting point for subsequent 3D data fitting model construction. As this model is intended to predict combustibility properties of burning particles in flight the data points corresponding to zero flow velocity were excluded from the analysis, therefore the model is applicable for surrounding flow conditions U>2m/s.

Through the 2D analysis, exponential, polynomials and rational functions have been recognized as the best fitting function types, which yield higher correlation coefficients. Due to the physical nature of the data to be fitted (k_0 and t_2 assume essentially positive values), the exponential function has been assumed as the most adequate function for subsequent construction of the fitting model.

The 3D data analysis was performed with the LAB Fit program (Silva W.P, Silva C.M, V 7.2.46, 1999-2009). Curve fitting has been done using the Levenberg-Marquardt algorithm. A unitary reduced chi-square value (Red χ^2) was employed as a goodness-of-fit metric. The ten best fitting models based on the program intrinsic library functions with up to 4 parameters were identified. These models were found to be mostly exponential and second and third degree polynomials functions, thus confirming the results we obtained from the 2D data analysis and providing us with a good starting point for the development of a custom fitting model. In order to improve the program library based fitting models, the following two additional functions have been tested:

$$z = a_1 + a_2\theta + a_3\theta^2 + a_4U + a_5U^2 + a_6\theta U \tag{2}$$

$$z = \exp(a_1 + a_2\theta + a_3\theta^2 + a_4U + a_5U^2 + a_6\theta U). \tag{3}$$

The relative quality of the models was judged by comparison of the corresponding correlation coefficients *Ryy(x)*.

The best fit in terms of *Ryy(x)* for both exponential mass loss coefficient k_o and duration t_b of SC was given by equation (3). The coefficients of the proposed model (3) for each one of six parameters are given in Table 1.

Table 1. Coefficient values for fitting model Equation (3) (U>0)

Part.	Param.	Correl. Coef. *Ryy(x)*	Fitting Stand. Dev.	Coefficient values					
				a_1	a_2	a_3	a_4	a_5	a_6
PC	t_b	0.980	95.44	6.21E0	4.3E-2	-4.6E-4	-2.4E-1	-2.8E-2	3.5E-3
	k_o	0.986	0.62	1.09E0	1.1E-2	-2.5E-4	-0.5E-1	-8.8E-3	9.8E-3
EB	t_b	0.595	40.71	5.35E0	1.4E-1	-5.9E-5	-3.9E-1	5.5E-2	-2.9E-3
	k_o	0.953	1.89	-3.04E0	3.8E-2	8.5E-5	1.11E0	-7.5E-2	-4.2E-3

Although the present model was developed with data obtained in tests with permanent boundary conditions – constant values of θ and U – it should be applicable to model the combustion of particles in varying conditions of flow velocity and incidence. Preliminary tests showed that the model predictions are quite good for PC but for EB the values of k_o are usually under predicted. The reason for this must be related to a faster response of the EB particles to changes of boundary conditions associated to a "memory" effect of the previous burning conditions that were not the same as those of the present tests.

6. CONCLUSION

The combustibility of particles that can be potential embers or firebrands is greatly dependent on their surrounding flow, namely on its reference velocity and direction. Particles that are ignited by a flame ignition source are consumed during its flight time at a rate that depends on the type of combustion regime and on the flow properties. In the present research program combustibility properties of two types of particles of *Pinus pinaster* and *Eucalyptus Globullus* that can be potential embers were studied experimentally in a vertical combustion tunnel and a test platform.

Depending on the properties of the particle, the orientation and of the flow, the firebrand can be entirely consumed in the combustion phase or we can have flame extinction and slow or glowing combustion that usually lasts for longer time. Duration of combustion for EB was generally in the range between 20 and 1100 seconds in the case of U=0 m/s; for test with wind 20s<t_b<200s. We observed that this property depends very much on the degree of convolution of the particle. In the absence of wind EB particles did not sustain flaming combustion for negative values of θ. On the other hand the duration of glowing combustion of EB particles has a range one order of magnitude above that of flaming combustion of these same particles.

Burnout time of PC varied between 100 and 1100 s and was greatly dependent not only on the flow velocity and direction but also on the properties of the PC such as its moisture content and the degree of opening of its scales.

Exponential mass loss coefficients for each particle varied with flow velocity and direction. In some cases like for k_o this variation covered a range of two orders of magnitude putting in evidence the need to have a good estimate of these parameters to predict correctly the mass loss of the particle. In general terms it is observed that the values of these coefficients decrease in the negative range and increase in the positive range of the orientation angle. Using the proposed models it is possible to estimate the duration of the combustion for the particles that were analyzed and to predict the mass loss decay during the flight of the particle as a function of local wind velocity and particle orientation in relation to this flow.

The present model was developed for application in the prediction of combustion of embers flying in changing boundary conditions. Some preliminary tests showed that it behaves well for PC while for EB it under estimates the value of k_o. This matter is now under investigation by the authors.

Further research is necessary to analyze the influence of particle properties like the moisture content, the degree of opening for pine cones or the degree of convolution for eucalyptus bark to better explain the scatter of the present data. This study should also be extended to similar particles of other species and to other types of particles.

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