Flame geometry and surface to crown fire transition during the propagation of a line fire through a Mediterranean shrub

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ABSTRACT: The effectiveness of fuelbreaks depends strongly on the fire spread conditions (rate of spread, flame height) through the shrub on the ground and also on the conditions of transition from a surface fire to a crown fire. This study is based on numerical simulations (using a multiphase approach) of fire propagation through a Mediterranean shrub. The geometry of the flame is defined from the energy loss in the gas resulting from the radiation emission of soot particles, the flames contours are reconstructed from a threshold level fixed to 60 kW/m$^3$. The flame geometry can be characterized by two length scales, the height $H_f$ and the length $L_f$ which can be compared to experimental results obtained for static or propagating fires. Extensive calculations have been first performed through a shrubland (Quercus coccifera + Brachypodium ramosum) for various fuel depth $H_{fuel}$ range from 0.25 to 1 m and for wind speeds $U_H$ ranging between 1 and 10 m/s. Then this study has been extended to situations including a supplementary fuel layer representing the head of small trees (Pinus halepensis). These numerical results have been analyzed introducing a dimensionless physical parameter, the Froude number, defined as the ratio between the wind flow inertial forces and the buoyancy. The results obtained with a upper fuel layer show the role plays by radiation heat transfers for the transition of the surface fire to the crown. Some calculations have been also performed to study the effects of a fuel reduction on the ground upon the vertical fire transition.

1 INTRODUCTION

The many studies developed these thirty last years on forest fire propagation modeling aim to understand fire behavior according to the conditions (meteorology, state of the vegetation, topography of the ground) which it meets during its progression. To reduce wildfire hazard, especially in natural zones situated in the vicinity of large cities in the urban/rural interface or along communication way, one solution is to reduce surface fuel which represents the first vector during fire ignition. To reduce the damages caused to the vegetation by a forest fire, one can carry out a fuel management policy (fuel reduction, fuelbreak ...) to reduce fire intensity and to limit the possibilities of transition from a surface fire to a crown fire (Agee & al 2000). Last years a new approach of landscape fuel management (shaded fuelbreak) has been promoted, retaining an opening forest canopy (trees are partially removing). The effectiveness of these shaded fuelbreaks remains a subject of debate, one difficulty is to evaluate the potential of vertical fire transition as a function of the surface fuel depth and the height to the base of the live crown. To answer to this
question we have to evaluate the flames geometry during the propagation of a wildfire according to
the surface fuel characteristics (nature, moisture content, depth), the meteorological conditions
(wind speed, ambient temperature …), the ground topography. The geometrical parameters which
define the characteristics dimensions of the flame (Thomas 1963) are the flame length \( L_f \) (measured
from the flame tip to the mid depth of the solid fuel), the flame height \( H_f \) (vertical projection of the
flame) and the flame tilt angle \( \Phi \) (see Figure 1).

![Figure 1: Wildfire propagation through shrub fuels: flame geometry.](image)

This paper is divided in two parts, the first one is devoted to the study of the flames characteristics
of a surface fire propagating through a Mediterranean shrub fuels (\( Quercus coccifera + Brachypodium ramosum \)). This problem is solved numerically using a multiphase complete
physical model (Morvan & al 2001, Morvan & al 2002), the visible flame contours are evaluated
from a threshold level of the radiation energy loss resulting from the formation of soot particles in
the flame. Then the structure of the vegetation is modified adding a solid fuel layer representing the
head of small trees (\( Pinus Halepensis \)), to study the effects of surface fuel reduction on the
transition between a surface fire and a crown fire.

The fire behavior model used for these numerical simulations are based on the resolution of
thermodynamics balance equations (mass, momentum, energy) which govern the evolution of the
coupled system form by the solid fuel families representing the vegetation and the surrounding gas
mixture (ambient air + pyrolysis and combustion products). All the mathematical details are
reported on the companion paper (Morvan & al 2002).

2 NUMERICAL RESULTS OBTAINED FOR THE SURFACE FIRE

We have studied the fire propagation through a shrub fuels composed as follows:
- \( 0 < z < 0.25 \) m \( Brachypodium ramosum \) (packing ratio 0.1%, moisture content 5%)
- \( 0 < z < H_{fuel} \) \( Quercus coccifera \) (packing ratio branches: 0.1%, leaves: 0.15%, moisture content 70%),

The calculations are performed for a surface fuel depth \( H_{fuel} \) ranging between 0.25 and 1m and for
wind speed \( U_H \) ranging between 1 and 10 m/s. As mentioned previously the visible flame contours
are reconstructed from the energy loss by radiation in the flame. The energy density level
representing the position of the flame is fixed to 60 kW/m³, which corresponds to the radiation heat
loss observed for a gas temperature equal to 900 K.
The results represented on Figure 2 show the flame contour evaluated using this method and the gas temperature calculated for a wind velocity $U_H = 5$ m/s. One can note on this figure the rolling up of the flame under the action of vortices resulting from the interaction between the convective column and the wind. Regularly pockets of ignited gas is detached from the flame front and come to ignite the vegetation downstream.

Figure 2: Flames contours and gas temperature calculated during the propagation of a surface fire.

The variations of $H_f$ and $L_f$ as a function of the wind speed is shown on Figure 3, we can notice that for $U_H \leq 6$ m/s, the flame length $L_f$ increases with the wind speed, then for stronger wind conditions we observe a sharp reduction of the flame expansion. The modification of the flame behavior has been also observed experimentally by Nelson & al (1986) for both laboratory and ground fires. This phenomenon is attributed to the competition between the buoyancy flow due to the vertical expansion of the hot gases above the combustion zone and the inertial flow induced laterally by the wind. The ratio between these two forces can be represented using a dimensionless physical parameter, the Froude number $F_r = \frac{U_H^2}{gH_fuel}$. This fire behavior transition corresponds also to a modification of the dominant mechanism of heat transfer between the fire and the unburned solid fuel, with the enforcement of the wind conditions the fire propagation is mainly controlled by convection (Pitts 1991, Morvan & al 2002).
Figure 3: Wildfire propagation through a Mediterranean shrub: variations of the flame height ($H_f$) and the flame length ($L_f$) as a function of the wind speed $U_H$.

The geometrical characteristics of the flame obtained numerically can be compared to experimental results measured on flames propagating through fuel beds or for gaseous flames generated from porous burner. Various experimental observations have shown that the vertical expansion of hot gases above the combustion zone (the plume) constitutes an obstacle which affects the side flow generated by the wind. The evolution of the flame tilt angle $\Phi$ (in fact $\tan(\Phi)/\cos(\Phi)$) as a function of the Froude number $F_r$ is represented on Figure 4 (left). Previous theoretical analysis (Fang 1969) has shown that the tilting angle $\Phi$ of a propagating wildfire verifies the following relation:

$$
\frac{\tan(\Phi)}{\cos(\Phi)} = \frac{L_f \sqrt{L_f^2 - H_f^2}}{H_f^2} = C_D \frac{U_H^2}{gD}
$$

(1)

where $C_D$ includes the effect of the flame drag coefficient and the density ratio between the gaseous fuel and the ambient air, $D$ is a characteristic fire dimension. For forest fuel bed, Fang (1969) has found experimentally a value for $C_D = 1.54$ which can be compared to the following expression obtained from the present calculation:

$$
\frac{\tan(\Phi)}{\cos(\Phi)} = 1.50 \left( \frac{U_H^2}{gH_{fuel}} \right)^{1.017} \quad (U_H < 6 \text{ m/s})
$$

(2)

Extrapolating the evolution of the flame length $L_f$ with the wind speed $U_H$ (see Figure 3), we can evaluate $L_f^0$ corresponding to the limit value as $U_H$ tends to zero, and we find (for $H_{fuel} = 0.5$ m) $L_f^0 \approx 1.73$ m. The variations of the ratio $H_f / L_f^0$ with the Froude number $F_r^0 = \frac{U_H^2}{gL_f^0}$ is presented on Figure 4 (right), which can be summarized using the following expressions:

$$
\frac{H_f}{L_f^0} = 0.665 \left( \frac{U_H^2}{gL_f^0} \right)^{-0.202} \quad \text{(present calculations)}
$$

(3)
\[ \frac{H_f}{L_f^0} \propto \left( \frac{U_H^2}{g L_f^0} \right)^{-\frac{1}{4}} \] (Experimental correlation, Putnam 1965)  

Where the last expression has been obtained for gaseous diffusion flames expanding from porous burner (Putnam 1965).

To study the potentiality of a vertical fire transition between the surface fuel and the crown, we have reported on Figure 5 the variations of the ratio \( \frac{H_f}{H_{fuel}} \) as a function of the Froude number \( F_r = \frac{U_H^2}{g H_{fuel}} \).

Figure 4: Flame tilting angle \((\tan(\Phi)/\cos(\Phi))\) as a function of the Froude number \( F_r = \frac{U_H^2}{g H_{fuel}} \) (left); \( \frac{H_f}{L_f^0} \) ratio as a function of the Froude number \( F_r = \frac{U_H^2}{g L_f^0} \) (right).

Figure 5: Flame height / fuel depth ratio as a function of the Froude number \( F_r = \frac{U_H^2}{g H_{fuel}} \).
Power law approximation of this curve shows that this dimensionless flame height varies as follows:

\[
\frac{H_f}{H_{\text{fuel}}} = 3.27 \left( \frac{U_H^2}{gH_{\text{fuel}}} \right)^{-0.265}
\]

(5)

For the conditions used in the present calculations, the flame height varies from 1.4 to 3.5 times the fuel depth on the ground. For stronger wind conditions (Fr > 10) the flame trajectory is significantly deviated by the wind flow and its vertical expansion is significantly reduced and the flame height / fuel depth ratio reaches a quasi asymptotic value around 1.4.

3 SURFACE FIRE TO CROWN FIRE TRANSITION (EFFECTS OF FUEL REDUCTION)

We have studied the transition between a surface fire propagating through the same shrub fuel described in the previous part and a crown situated 2 m height above the ground level representing the head of small trees (Pinus Halepensis) (see Figure 6). This new fuel layer is represented using two families of fuel particles: small branches (Surface/Volume = 4000 m$^{-1}$, density = 900 kg/m$^3$) and pine needles (Surface/Volume = 10000 m$^{-1}$, density = 680 kg/m$^3$). The moisture content and the packing ratio for the two solid fuels families are respectively equal to 70% and 0.5 %

Figure 6: Surface fire to crown fire transition in a shaded fuelbreak.

The results presented on Figure 7 show the evolution of the gas temperature calculated during the propagation of a wildfire through a shrubland (H$_{\text{fuel}}$ = 0.5 m) under a Pinus Halepensis canopy, and for a wind speed U$_H$ = 4 m/s. These results highlight the ignition of the crown above the surface fire. Taking into account the localization of the ignition point in the upper fuel layer and of the trajectory of the hot gas plume, it seems obvious in this case that the fire transition from the ground to the crown results from radiation heat transfers coming from the flame. For a wind speed U$_H$=4m/s the flame height H$_f$ (equation 5) varies with the surface fuel depth as follows: $H_f = 3 \times H_{\text{fuel}}^{2.65}$ (H$_f$ = 1.25m for H$_{\text{fuel}}$=0.5m, H$_f$ = 0.52m for H$_{\text{fuel}}$=0.25m , H$_f$ = 0.27m for H$_{\text{fuel}}$=0.15m). Empirical observations have shown that for a height of crown base equal to 2m, and
a foliar moisture content equal to 70%, the flame height associated with initiating crown fire is 1.1 m (Agee 1996, Agee & al 2000). The temperature fields calculated for three values of the fuel depth $H_{fuel}=0.5$, 0.25 and 0.15 m (Figure 8) show the effectiveness of the surface fuel reduction to prevent crown fire ignition. These results are confirmed on Figure 9 representing the time evolution of the flame height ($H_f$) for the three cases. As the flame height reaches a critical value equal to 1.1m (conform to the value observed empirically), one can note the ignition (Figure 8 on top, $H_{fuel} = 0.5$m) or the formation of a hot spot (Figure 8 on middle, $H_{fuel} = 0.25$m) on the base of the upper fuel layer.

Figure 7: Evolution of the gas temperature calculated during the propagation of a surface fire through a shrubland under a Pinus Halepensis canopy (fuel depth = 0.5m, wind speed = 4 m/s).
Using the packing ratio which characterized each component of the shrub fuel, we can evaluate an average fuel volume, for $H_{\text{fuel}} = 0.5$ m this value is equal to 5000 m$^3$/ha. The foresters estimate empirically that safety conditions are assured for an average fuel volume of 1000 m$^3$/ha, for a value range between 2000 and 2500 m$^3$/ha a new fuel reduction treatment is necessary. The present calculations confirm these empirical laws, for a surface fuel volume of 1500 m$^3$/ha no...
surface/crown fire transition is observed and for a value equal to 2500 m$^3$/ha the apparition of a hot spot at the base of the canopy seems to indicate that a vertical fire transition can occur.

Figure 9: Time evolution of the flame height calculated for three values of the surface fuel depth $H_{\text{fuel}}=0.5, 0.25$ and $0.15$ m.

4 CONCLUSIONS

We have performed numerical simulations representing wildfire propagation through a Mediterranean shrub using a multiphase formulation. Flames characteristics evaluated from energy loss by radiation are in good agreement with experimental observations on propagating fires and for static gaseous diffusion flames. These calculations have been generalized to study the surface to crown fire transition. The numerical results show the effectiveness of fuel reduction to prevent surface to crown fire transition, and confirm for these particular conditions the empirical criteria used by foresters.

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