THE IMPORTANCE OF FIRE FRONT WIDTH IN THE ANTICIPATION OF ERUPTIVE FIRES

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Abstract

Fire eruption is a significant threat to the safety of wildland fire fighters. Over the last few years, several accidents have caused important human losses. Generally, these fire fighters are surprised by the sudden acceleration of the head fire and they are not prepared for facing it. We characterize eruptive fires by an unexpected increasing of the head fire in a short lapse of time. Despite the danger of the phenomenon, fires rarely erupt and consequently studies of the mechanisms contributing to fire eruption are not so numerous. A recent paper [1] reviewed them in two ways: explanations are mainly based on a variation of the external conditions or on the spreading fire's own properties.

Our interpretation about the mechanism leading to a possible eruption consists in an induced air flow created by the fire. We use a semi-physical steady-state model with two equations, which are coupled by this induced wind. This coupling is solved thanks to a fixed-point method and it converges under certain conditions (or does not). In the divergence case, the rate of spread grows infinitely. So the model is not able to describe the fire behaviour during the eruption but it is possible to give the precise conditions for the occurring of the eruption.

When meteorological conditions and fuel bed properties are known, we can find the slope angle at which a fire, with given dynamic parameters (fire front width, flame length), erupts. In particular, we will pay interest in the influence of the fire front width on the condition leading to eruption.

We validate the model on two sets of experiments at the laboratory scale and a real accident, happened on the Kornaty Islands, Croatia, 2007.

Additional Keywords: Eruptive fire, unsteady solutions, fire spread, physical model.

Introduction

The spread of a wildfire is more important up a slope than it will on a flat terrain. But sometimes, this usual behaviour can turn into an extreme situation with a sudden and important acceleration of the head fire. Some explanations are given in the literature to define this significant change.

The pioneering interpretation, proposed by Viegas [2], consist in a positive feedback from the fire. The convective flow induced by the fire front in the presence of wind or on a positive slope transports oxygen to the reaction zone. This one intensifies the combustion process and consequently the flame length and the rate of spread. So the reaction needs more and more ambient air. This feedback process will increase continuously and the rate of spread could reach very important values if it is not inhibited by some external mechanism.

The concept of flow attachment is more recent [3,4,5]. It distinguishes eruptive fire from a steadily spreading fire (where buoyancy drives the hot gases of the fire upwards). So unlike a steady fire spread where air streams, in front of, and behind the fire, meet to be finally separated from the slope, when a fire erupts the flow remains attached to the slope and rises up to it.
In this paper, our explanation of the eruption phenomenon is similar to the two previous ones. The modeling is based on an induced air flow created by the fire on a positive slope in order to supply the combustion process with oxygen.
We assume this induced wind is the mainspring of the mechanism leading to eruption. The induced wind is proportional to the rate of spread and the rate of spread is in a non-linear relationship with the induced wind. This feedback can converge or diverge in certain conditions.
We use the Balbi et al simplified semi-physical model [6,7,8]. This physical model has proved its efficiency in correctly reproducing some fire experiments both at laboratory and field scales [7], even when wind velocity is important [8]. This steady-state model is not able to describe the fire behaviour during the eruption because the steady fire spread growth is infinite but it will give the conditions of its occurring. We will give the divergence conditions according to meteorological and topographic parameters, fuel bed properties and the fire dynamics. For a set of given parameters, it may exist a critical slope angle at which the flame tilt angle tends towards 90°. This slope angle can be regarded as the concept of flame attachment to the slope, as Dold described [3,4].

The simplified semi-physical model

The model takes into account the radiation of the burning fuel bed (R_b) and the radiation from the flame above the vegetal stratum (R_f). It gives the main physical values (flame tilt angle γ, rate of spread R, flame height H and temperature T).
The main equations for a head fire (positive flame tilt angle) depend on the slope angle α, the normal wind velocity U and the upward gas velocity u_0:

$$\tan\gamma = \tan\alpha + \frac{U}{u_0} \tag{1}$$

$$R = R_b + R_f \tag{2}$$

with

$$u_0 = \nu\left(8\frac{s_t+1}{\tau_0}\frac{\rho_v}{\rho_a}\frac{T}{T_a}\right) \tag{3}$$

$$\nu = Min\left(\frac{S}{4};1\right), \qquad S = s\,e\,\beta \tag{4}$$

$$T = T_a + \frac{\Delta H}{(s_t+1)C_{pa}}\left(1-\frac{\chi_0}{2A}\right) \tag{5}$$

$$R_b = \frac{e}{\sigma}\frac{BT^4}{C_p\Delta T + m\Delta h} \tag{6}$$

$$R_f = A\,R\frac{1+\sin\gamma-\cos\gamma}{1+\dfrac{R\cos\gamma}{r_0}} \tag{7}$$

$$A = \nu \frac{\chi_0 \Delta H}{4(C_p \Delta T + m\Delta h)} Y; \qquad Y = \tanh\left[\frac{2}{3}\left(\frac{W}{l}\right)^{\frac{1}{3}}\right] \tag{8}$$

$$r_0 = s\, r_{00} \tag{9}$$

$$H = \frac{2\chi_0\, \Delta H\, r_{00}\, \rho_v}{BT^4} \nu \tag{10}$$

Equations (3-10) depend on meteorological conditions and parameters (ambient temperature T_a, ignition temperature T_i, specific heat of the air C_{pa}, air density ρ_a), fuel bed properties (density of the vegetal ρ_v, surface area to volume ratio of fuel elements s, fuel bed thickness e, packing ratio β, fuel load σ, moisture content m and heat of combustion of the pyrolysis gases ΔH) and dynamic fire parameters (fire front width W, flame length l).

The parameter r_{00} is an empirical parameter. It has been fitted on all the set of experiments carried out in [7] ($r_{00} = 2.5.10^{-5}$ m^2.s^{-1}). The value of the parameter χ_0 is equal to 0.3 [9]. We denote by τ_0 (τ_0 = 75591 s.m^{-1}), the parameter of the Anderson's expression of the time residence [10].

We can notice [11] that the analytic solution of eq. (2) can be easily found:

$$R = \frac{r_0}{2\cos\gamma}\left(R_b \frac{\cos\gamma}{r_0}\big(A(1+\sin\gamma-\cos\gamma)-1\big) + \sqrt{\left(R_b \frac{\cos\gamma}{r_0}\big(A(1+\sin\gamma-\cos\gamma)-1\big)\right)^2 + 4R_b\frac{\cos\gamma}{r_0}}\right) \tag{11}$$

The value of the parameter A involves the fire propagation dynamic:

- When A < ½, the rate of spread is bounded by $R_\infty = \dfrac{R_b}{1-2A}$ (left part of fig. 1).
- When A > ½, the rate of spread has a straight-line asymptote (right part of fig. 1). Its equation is given by:

$$R_\infty = p_\infty\,(\tan\gamma - b_\infty) \text{ and } p_\infty = r_0\,(2A\text{-}1) \tag{12}$$

This value p_∞ will be important in the condition of eruption. The case A = ½ leads to the condition $R_\infty = (R_b r_0)^{\frac{1}{2}}(\tan\gamma)^{\frac{1}{2}} + R_b - \frac{r_0}{2}$.

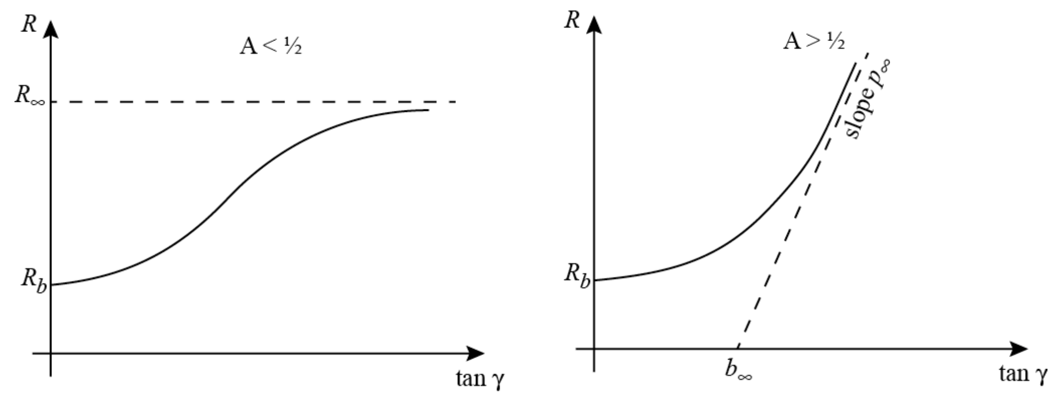


Figure 1. The two kinds of behaviour of the ROS R as a function of the flame tilt angle.

Fire-induced wind sub-model

For steep slopes ($\alpha > 10°$) and weak wind velocity ($U < u_0 \tan \alpha$), the fire creates an induced airflow U_i in order to fill in the draught caused by the hot gases moving upwards. This fire-induced wind will play a major role in the occurence of eruption.

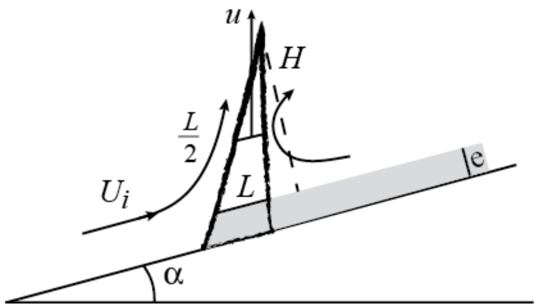


Figure 2. A qualitative illustration of the flame geometry.

We determine it from a mass balance in the flame between the top of the vegetal stratum and the half-height. We neglect the rate of flow of the pyrolysis gases with regard to the rate of flow of the air coming in the flame (they are in a stoichiometric rate $s_t \approx 8.3$). The induced air flow in front of the fire does not have an influence in the mass balance. So with ρ the combustion gases density, ρ_a the air density, L the flame depth, H the flame height and u the upward gases velocity with slope (see fig.2), we have:

$$\rho_a \frac{H}{2} U_i = \rho \frac{L}{2} u \cos\alpha \qquad (13)$$

As [7], $$u_0 = u \cos \alpha$$

We obtain $$\frac{U_i}{u_0} = \frac{\rho}{\rho_a}\frac{L}{H} = \frac{\rho}{\rho_a}\frac{R\tau}{H} = \frac{R}{p},$$

So the relationship (1) is replaced by

$$R = p\,(\tan \gamma - \tan \alpha) \qquad (14)$$

with

$$p = 2\frac{\chi_0\, \Delta H\, \rho_v\, \nu\, r_0}{B T_a T^3 \tau_0} \qquad (15)$$

Theoretical analysis

We use a fixed-point method to solve the coupled equations (14) and (2) and we denote by (R_0, γ_0) the initial value. We will make a qualitative graphic analysis of the two functions given by these equations. We distinguish four different cases:

1st Case: $A \leq ½$

Whatever the values of the various parameters, the graphic resolution (fig. 3) of the two equations (14) and (2) shows a bounded unique solution. So, when $A < ½$, the eruption is impossible. When A = ½, the graphic resolution of the equations (14) and (2) always shows a unique solution. But due to the expression of the asymptote, this solution can be large but always finite. Nevertheless the eruption remains impossible.

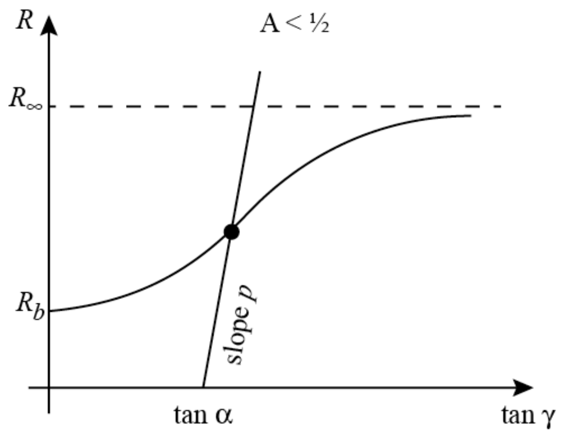
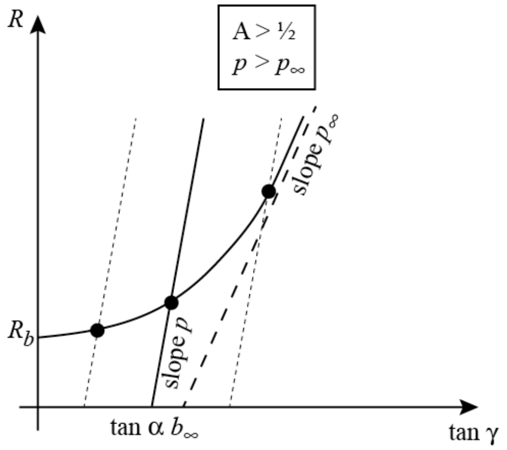


Figure 3. Graph of the ROS as a function of the flame tilt angle with A smaller than ½.

2nd Case: $A > ½$ and $p > p_\infty$
It is clear (left part of fig. 4) that if the slope p is greater than the asymptote slope p_∞, we obtain a unique solution for each slope angle α. This solution can be large but is always finite. So an eruption is impossible.



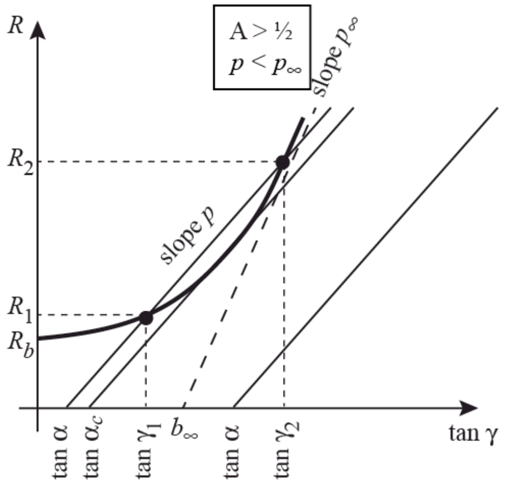


Figure 4. Graph of the ROS as a function of the flame tilt angle with A greater than ½.

3rd Case: $A > ½$, $p < p_\infty$ and $\alpha < \alpha_c$
We can observe on the right part of fig. 4 that if the slope p is smaller than the asymptote slope p_∞ and if α is small enough, we obtain two different solutions. For a specific value α_c, the straight-line corresponding to (14) is tangent to the curve given by (2). The first solution (corresponding to (R_1, γ_1)) is stable with regard to the initial conditions (R_0, γ_0), provided that these ones are respectively smaller than R_2 and γ_2. So we obtain a non-eruptive bounded solution (R_1, γ_1). If the initial conditions (R_0, γ_0) are respectively greater than R_2 and γ_2 we observe a divergent solution that involves an eruption. So in this case, an eruption is possible but not very probable because we need strong initial conditions (wind, ignition…). In fact, the closer α gets to α_c, the faster an eruption is probable.

4th Case: A > ½, $p < p_\infty$ and $\alpha > \alpha_c$
When $\alpha > \alpha_c$ (right part of fig.4) a steady solution of the equations (14)(2) does not exist. In fact, we obtain an unsteady divergent solution, whatever the initial conditions. In this case, an eruption is assured.

Conditions leading to eruption

When the eruption occurs, the steady rate of spread tends towards infinity. We have reached the limit case of the model. But the model is able to give a physical explanation of the eruption phenomenon and to predict the occurring of the eruption. As we have seen in the theoretical analysis, a fire eruption can occur only when $p < p_\infty$.

First condition: $p < p_\infty$

With (8)(12) and (15), this first condition can be written as:

$$\frac{p}{p_\infty} = \frac{\rho_v}{\tau_0 B T_a T^3 \left[\dfrac{Y}{4(C_p \Delta T + m\Delta h)} - \dfrac{1}{2\nu \chi_0 \Delta H} \right]} < 1 \qquad (16)$$

Several factors contribute to satisfy the relationship (16):

- Fuel bed properties
  - The relationship (16) will be easier satisfied for a light vegetal, where its density ρ_v and the specific heat of vegetative fuel C_p are weak. For example, grass is more eruptive than a *pinus halepensis* layer.
  - A vegetal with a weak ligneous component contributes to eruption. Indeed, the heat of combustion of the pyrolysis gases can be written as $\Delta H = \Delta H_T - c\ \Delta H_c$, where ΔH_T is the heat of combustion of fuel ($\Delta H_T \approx 1.8.10^7$ J.kg^{-1}), c the percentage of chars and ΔH_c the heat of combustion of the charcoal. So, the less the charcoal, the greater ΔH is, and then the ratio given by (16) decreases because of the explicit expression of ΔH in (16) and in a major part with the temperature T^3 which strongly increases with ΔH (eq. 5).
  - A sufficient fuel load. Coefficient ν must be as great as possible, i.e. equal to 1, due to its definition (eq. 4). So the leaf area index S must be greater than 4. As $S = \frac{s\sigma}{\rho_v}$, a light (weak density) and thin (important surface area to volume ratio) vegetal satisfies this condition with a minimal fuel load of $\frac{4\rho_v}{s}$. For the example of a grass layer, to reach $\nu = 1$, if $\rho_v = 400$ kg.m^{-3} and $s = 10000$ m^{-1}, the minimal fuel load must be equal to 0.16 kg.m^{-2}.
  - A dead vegetal stratum. Indeed, the moisture content m will be weaker than the moisture content of a living vegetal stratum.
- Environmental factors
  - A high ambient temperature. T_a plays a direct part in (16) but also through $\Delta T = T_i - T_a$ and through T (Eq. 5). But T_a might play a part through T_i. If the summer temperatures are extreme (≈ 40°C), we know [12] that some volatile organic compounds are probably emitted in a sufficient quantity to burn at a temperature lower than the usual temperature given for T_i (600 K). This study deserves to be deepened and it would be useful to have a law for ΔT as a function of T_a.
  - A weak relative humidity. Indeed, the moisture content is an increasing function of the air humidity [13].
- Factors linked to the fire dynamics
  - A strong coefficient Y (close to 1). The condition (16) is very sensitive to this coefficient and its effect will be detailed separately.

Second condition:

When the condition $p < p_\infty$ is satisfied, the possible or sure eruption characteristic depends on another criterion, the comparison between the slope angle α and the critical slope angle α_c. It is not possible to determine the analytic value α_c, which correspond to the tangent to the curve R given by (2) with a slope p. But the numerical study presented in the next section shows that:

$$\tan\alpha_c = \frac{p}{p_\infty} - 0.25 \tag{17}$$

So we obtain two different cases:

- If $\tan\alpha < \frac{p}{p_\infty} - 0.25$, eruption is possible only if the initial condition γ_0 is greater than the value γ_2. This case might happen if a strong and long gust sets $\gamma_0 > \gamma_2$. When the divergence is started, it will continue, even if the gust stops (because the ratio $\frac{p}{p_\infty}$ is not changed). This condition is all the more difficult to satisfy since p is close to p_∞ and α is small because γ_2 becomes closer to 90°.
- If $\tan\alpha > \frac{p}{p_\infty} - 0.25$, the steady solution is diverging whatever the initial conditions. The eruption is certain.

The effect of the fire front width

The fire front width W influences the coefficient Y (eq. 8). Let us remind that the modelling of the flame radiation is based on the assumption of an infinite radiant panel [6,8]. Obviously the panel is finite and this coefficient Y is a corrective term which allows using the assumption of a finite radiant panel in the modelling of the coefficient A and gives good agreement with 3D view factors [14].

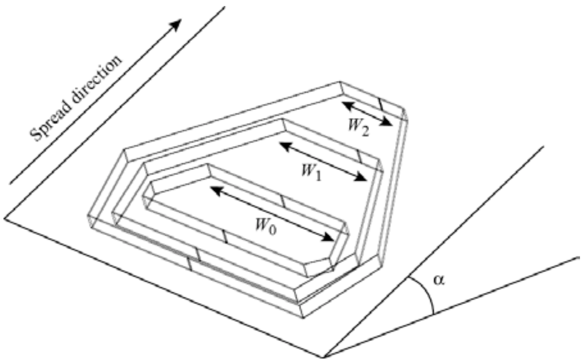


Figure 5. A qualitative presentation of the evolution of the fire front width during the spread, at different time steps.

The ratio $\frac{p}{p_\infty}$ is very sensitive to the value of this parameter W. The ideal situation happens when Y is close to 1, i.e. the fire front width is much greater than flame length ($W >> l$). But this width will generally decrease with time. Indeed, if W_0 is the initial width, after a certain time, the fire front width will only be W_1 (see fig. 5) and then W_2 etc… This sharp-shaped effect is due to the velocity of the fire front edges, which is smaller than the velocity of the fire front centre because:

- The edges of the fire front only receive the radiation from one half of a radiant panel. So the parameter A is divided by 2 and the ROS R strongly decreases.

- On the edges of the fire front, there is an additional air flow entry, with regard to the mass balance done in (13). So the induced wind U_i, which is normal to the front will be weaker and so on the tilt angle γ and the ROS R.

So the eruption condition $p < p_\infty$ might be initially fulfilled but it vanishes when Y is weaker, preventing the next eruption somehow. If the initial fire front width W_0 is sufficient, the eruption is released. Thus, the ROS R will strongly increase and then the width W will fastly decrease until it stops the eruption when p becomes greater than p_∞.

Validation of the model

A simulation case

Before validating our model on real sets of experiments, we carried out several simulations in order to test the sensitivity of the condition (16) to the fluctuations of some parameters.
For the simulation case, we choose a straw layer such as a vegetal stratum with usual characteristic. Straw characteristics (table 1) contribute to a possible eruption.

Table 1. Fuel bed characteristics and meteorological conditions for the simulations

Parameter	*Value*
Density of the vegetal ρ_v	450 kg.m^{-3}
Specific heat of vegetative fuel C_p	1500 J.kg^{-1}.K^{-1}
Fuel moisture content m	10%
Surface area to volume ratio s	10 000 m^{-1}
Heat of combustion of the pyrolysis gases ΔH	1.3.10^{7} J.kg^{-1}
Fuel load σ	0.6 kg.m^{-2}
Ambient air temperature T_a	300 K

The coefficient Y (linked to W, the fire front width) is the only dynamic parameter.
We study the behaviour of the model with the variations of the parameter Y from 1 to 0.6 with a 0.01 step. For each value of Y, the slope angle α is varying from 0° to 50° (1° step) and we record the value of the first slope angle (α_c) leading to eruption. The results are given in table 2.

Table 2. The slope angle leading to the occurring of the eruption according to the value of the coefficient Y with a straw fuel bed.

Parameter Y	α_c (°)	p/p_∞	Parameter Y	α_c (°)	p/p_∞
1	17	0.5574	0.86	25	0.7427
0.99	18	0.5676	0.85	26	0.7604
0.98	18	0.5783	0.84	27	0.7789
0.97	19	0.5893	0.83	28	0.7983
0.96	19	0.6007	0.82	29	0.8186
0.95	20	0.6125	0.81	30	0.8399
0.94	20	0.6248	0.80	31	0.8623
0.93	21	0.6376	0.79	32	0.8857
0.92	21	0.6508	0.78	33	0.9104
0.91	22	0.6646	0.77	34	0.9364
0.90	23	0.679	0.76	36	0.9638

0.89	23	0.6939	0.75	38	0.9928
0.88	24	0.7095	< 0.75	No eruption	> 1
0.87	25	0.7258			

We can notice that the eruption occurs only when $p < p_\infty$. The eruption probability is increasing with the fire front width. Indeed, when the coefficient Y is small, there will be no eruption. If the fire front width is important (or the flame length is small), the fire behaviour can suddenly change even when the slope angle is relatively moderate (smaller than 20°). If we plot (fig. 6) tan α_c as a function of $\frac{p}{p_\infty}$, the interpolation straight line allows us to find an approximation of the limit case α_c:

$$\tan\alpha_c \approx \frac{p}{p_\infty} - 0.25$$

We validate our model with two sets of experiments at the laboratory scale and a real fire happened on Kornat island in 2007.

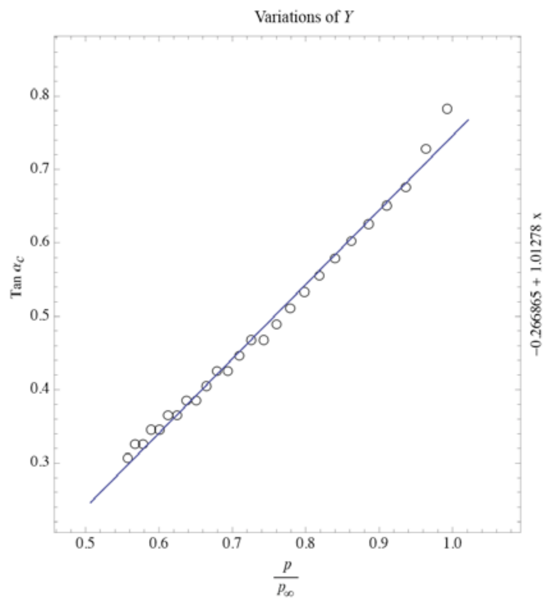


Figure 6. Plot of the slope angle α_c as a function of the ratio p / p_∞ with Y as varying parameter.

Opened inclination table

This set of experiments has been carried out by Rossa [15]. It consists in four different experiments at 10°, 20°, 30°, 40° slope angle, without wind. The conditions of the experiments are similar to the simulation case (straw as fuel bed, characteristics presented in table 1).

The author does not observe any eruption. This is due to the fast decreasing of the fire front width, especially with steep slopes. The ratio between fire front width and flame length becomes smaller with the increasing of the slope angle, and the fire front shape fastly becomes triangular.

We measured the fire front width and flame length at the same time for the four experiments, soon after ignition, when the steady state regime is established. It is the best moment to observe a possible eruption because the fire front width is still important and the flame length is short. The results are presented in table 3. Our simulation results confirm the non-eruption because the slope angle required for a fire eruption is greater than the slope angle of each experiment.

Table 3. Comparison between the slope angle required for a fire eruption and the experimental slope angle.

Slope angle	Ratio W / l	Parameter Y	Slope angle required for eruption
10°	7.64	0.86	25°
20°	4.93	0.81	30°
30°	0.42	0.46	No eruption
40°	0.17	0.35	No eruption

Confined inclination table

The CEIF laboratory of Prof. D.X. Viegas has carried out a set of experiments described by Dold [3,4]. The characteristics of the fuel bed used (straw) are the same as the ones we chose for the simulation case.

The inclination table is closed laterally by vertical walls. So these experiments simulate a large fire front. Indeed, these walls prevent lateral air flow entries from reaching the fire front and they reflect the radiation to increase the "virtual" fire front width.

Then, it is not easy to estimate precisely the coefficient radiation to increase the "virtual" fire front width and the coefficient Y, which should be important. In the same conditions, without lateral walls, the value of the coefficient Y is smaller than 0.8. So we assume it is about 0.8-0.9. Thus the simulations with our model show that an eruption will occur with a 26° slope angle for an average value of $Y = 0.85$ (table 2), i.e. $W / l = 6.68$.

The experiments carried out for Dold consist in five trench fire experiments at 15°, 20°, 25°, 30° and 35° slopes. For the three lower slopes, the fire is spreading in a usual way, but a very fast spread is observed for the two higher slopes. So eruption happens between 25° and 30°, which is in accordance with our simulated results.

The Kornaty fire accident

We talk about the biggest fire fighting accident that happened on the Kornaty Islands, Croatia in 2007. Unfortunately, this fire caused the death of 12 fire fighters, 1 being badly injured.

The full description of this accident is detailed in [16,17].

The vegetal stratum is a grass layer scattered with stones. The stratum's characteristics were almost equal to the ones we had chosen in the simulation case and according to the authors, a wide fire front (less than 100 m) reached the canyon with a moderate slope ($\alpha \approx 15°$). Eruption happens. The flames length was not very important (50 cm – 1 m). So the parameter Y is close to 1 in this case. We obtain the approximated value of 0.98 for Y.

Our simulation results with $Y = 0.98$ give the start of the eruption with a slope angle $\alpha = 18°$ (see table 3), which is in accordance with the average slope of the canyon.

On Kornat island, the fire was pushed by a S-E wind. But the melted particles of a fire-fighter found on a stone behind him prove that the wind generated by the fire was very strong and coming from the south. So the constant wind can be considered as a catalyst but it is not the mainspring of the eruption. The fire-induced wind which grows to be stronger than the S-E wind, is probably more important in the occurring of the eruption.

Conclusion and prospects

In this paper, we present the model developed by Balbi et al, with a new fire-induced wind sub-model whose role is crucial. This model is a simplified semi-physical model, constituted by two algebraic coupled equations giving the ROS R and the flame tilt angle γ. The time calculus is much shorter than in real time. This model leads to the following results:

- If the ratio $\frac{p}{p_\infty}$ (eq. 16) is greater than 1, there is no eruption.

- If the ratio $\frac{p}{p_\infty}$ (eq. 16) is smaller than 1, we obtain two different cases:
    - If tan $\alpha < \frac{p}{p_\infty}$ - 0.25, an eruption can happen only if the initial condition γ_0 is greater than a certain value γ_2 (large, close to 90°).
    - If tan $\alpha > \frac{p}{p_\infty}$ - 0.25, an eruption necessarily happens whatever the initial conditions.

The ratio $\frac{p}{p_\infty}$ (eq. 16) expresses itself from the vegetal characteristics, the meteorological conditions and the shape of the fire front.
The ideal conditions in order to have an eruption are:

- A light vegetal, weakly ligneous, with a sufficient fuel load, or a dead vegetal,
- Dry summer conditions,
- A large fire front or a fire in a canyon.

Let us notice that the fire front width is an essential dynamic parameter: for example, it is possible to obtain an eruption when a fire front that is wide enough reaches a breaking slope and then the eruption can stop (without any change in the slope angle) because a sharp-shaped effect will considerably reduce the fire front width.
This simple semi-physical model gives the description of the phenomenon leading the eruption and allows to precisely prevent it according to the vegetal and environmental characteristics.
Naturally, it is important to validate this model with several laboratory experiments and analysis of real eruptive fires, and this is what we plan to do in a next work.

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Nomenclature

Symbol	*Units*	*Description*
A		Ratio between incident radiant energy and ignition energy of wet fuel
B	W.m^{-2}.K^{-4}	Stefan-Boltzmann constant
C_p, C_{pa}	J.kg^{-1}.K^{-1}	Specific heat of the vegetative fuel, of the air
e	m	Fuel bed thickness
H, l, L	m	Flame height, Flame length, Flame base depth
m	%	Dead fine fuel moisture content
R	m.s^{-1}	Rate of spread
R_b	m.s^{-1}	Part of the rate of spread due to radiation of the burning fuel bed
R_f	m.s^{-1}	Part of the rate of spread due to flame radiation
r_0	m.s^{-1}	ROS factor
s	m^{-1}	Surface area to volume ratio of fuel elements
S, s_t		Leaf area index, stoichiometric coefficient
T, T_a, T_i	K	Flame temperature, ambient air temperature, ignition temperature
U, U_i	m.s^{-1}	Normal wind velocity, induced wind velocity
u, u_0	m.s^{-1}	Upward gas velocity with slope, on a flat terrain
W	m	Fire front width
α, γ	°	Slope angle, flame tilt angle
β, ν		Packing ratio, fuel bed absorptivity
χ, χ_0		Radiative heat loss fraction, Radiant factor

Δh	J.kg^{-1}	Heat of latent evaporation
ΔH, ΔH_T, ΔH_c	J.kg^{-1}	Heat of combustion of the pyrolysis gases, of fuel, of the charcoal
ΔT	K	$T_i - T_a$
ρ, ρ_v, ρ_a	kg.m^{-3}	Combustion gases density, combustible density, air density
σ	kg.m^{-2}	Fuel load
τ	s	Flame residence time
τ_0	s.m^{-1}	Anderson's flame residence time coefficient

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