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Physical modelling of fires spreading upslope, involved in fire eruption triggering

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Abstract

Eruptive fires are one category of extreme fire behaviour. They are characterized by a sudden and unpredictable change in the fire behaviour which represents an extreme danger for people involved in firefighting. The major point is about the mechanism that turns a usual fire behaviour into an eruptive fire behaviour. Among the different explanations found in the literature, the pioneering interpretation consisting in a feedback effect caused by the convective flow induced by the fire under wind and/or slope conditions, has never been disproved with an example of fire accident. The main goal of this work lies in proposing a physical modelling of this fire induced wind. This modelling attempt is derived from the brand-new version of the Balbi model, which is a simplified physical model for surface fires at the field scale that explicitly depends on the triangle of fire (fuel bed, wind and slope). This work is a first step to the modelling of fire eruption. The model tries to represent accurately the acceleration of the fire rate of spread propagating on different sloped terrain under no-wind or weak wind conditions. It is tested against three sets of experiments carried out at the laboratory scale without external wind and against a high intensity experimental fire spreading on a steep sloped terrain and conducted under weak wind conditions in the north-western of Corsica. Some statistical tools are used to compare predicted and observed rate of spread (NMSE, Normalized Mean Square Error and MAPE, Mean Absolute Percentage Error) and to understand the model's under-predictions or over-predictions trends (FB, Fractional Bias).

1. Introduction

A small part of wildfires (less than 2 per cent) (European Science & Technology Advisory Group 2020) has the most significant ecological and socio-economic impacts. These so-called extreme wildfire events ((Tedim *et al*. 2018) are characterized by very high fire intensities which lead to ineffective suppression capabilities. Eruptive fires are part of these extreme fire behaviours. If those eruptive fires are also known in the literature as flashover (in enclosed spaces, NFPA 921, 2011), blow-up (Butler *et al*. 1998) or generalized blaze flash (Chatelon *et al*. 2014), some slight differences remain between each definition. The definition of fire eruption has been proposed and characterized by Viegas (2004). It describes a fire with a sudden acceleration of the head fire rate of spread (ROS) in a very short time lapse with or without any changes in the topography, in the environmental conditions or in the vegetal stratum characteristics.

This phenomenon is very dangerous for firefighters and civilians because of its difficulty to be predicted and anticipated. Viegas and Simeoni (2008) reviewed the major mechanisms supposed to be the cause of a fire eruption triggering. For instance, from the firefighters point of view, an important release of VOCs (volatile organic compounds) is the main reason for a fire to erupt. Indeed, when a fuel is severely stressed, it releases VOCs that ignite a a lower temperature than the usual ignition temperature. The VOC's theory consists in assuming that a fire eruption is mainly caused by this gas release and is widely used in the literature (Chetehouna *et al*. 2014, Courty 2012). But the example of the Kornati fire accident (Viegas *et al*. 2008) refute this argument with a fire spreading across a grass fuel bed.

The pioneering interpretation proposed by Viegas (2004) consists in the presence of an air flow created by the fire itself which may significantly lead to a change in the fire behaviour, particularly for fires spreading upslope. The role of this induced convective flow is to bring fresh air and then oxygen to the flame in order to support the combustion. Viegas and Pita (2004) observed the importance of this air movement on the behaviour of fire spreads in canyons (at the laboratory scale and also during the field scale Gestosa fire experiments) and the accident occurred in Freixo de Espada-a-cinta (Viegas 2004) also support this interpretation.

So, a good modelling of the fire induced wind is the first step before trying to give a fire eruption physical model. In this work, the explanation provided by Viegas is selected and a first attempt of a physical modelling of this induced wind is proposed. It is based on a brand-new Balbi model formulation derived from (Chatelon *et al*. 2022) tested against more than 300 shrubland and grassland fires at the field scale with a very good agreement. This induced wind modelling is supposed to provide a good representation of a fire spreading upslope without wind (or with weak wind conditions). The model gives a new expression of the ROS that takes into account the pronounced acceleration of the fire spread with the increasing slope. It is tested against three different series of laboratory fire experiments (Butler *et al*. 2007, Liu *et al.* 2014, Liu *et al.* 2022) conducted without wind and in which the terrain slope angle varies ranges from 0 to 35° and against a field scale experimental fire conducted in Corsica across shrub species under weak wind and steep slope conditions (28°).

2. Physical modelling of the fire induced wind

2.1. Main equations of the new Balbi model

The Balbi model presented by Chatelon *et al.* (2022) calculates the ROS as the sum of three components (see fig. 1): (1) the radiation from the free flame F1 on the unburnt fuel (R_r), (2) the radiation from the flame base (the fuel burning particles area, R_b) and (3) the convection inside the vegetal stratum (R_c). The main equation of the model is the following:

$$R = R_b + R_c + R_r \tag{1}$$

The flame F2 is due to the flame base radiative and convective heat fluxes. All details and nomenclature can be found in (Chatelon *et al.* 2022).

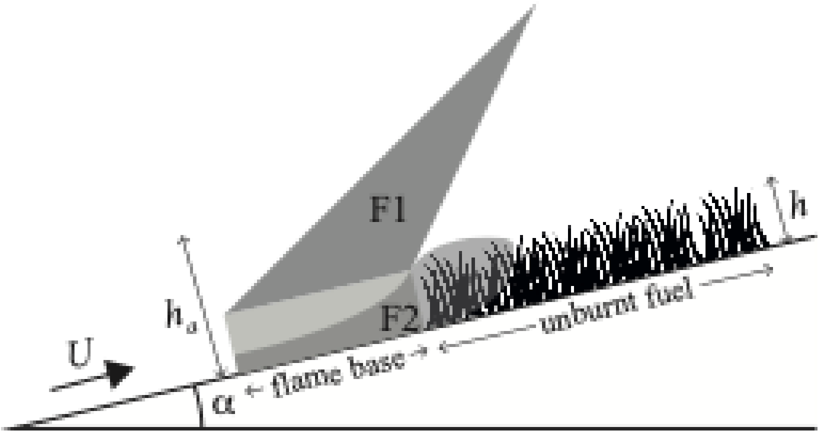

Figure 1- An idealized representation of the flaming zone combustion profile

As the convective and free flame radiative contributions to the ROS (R_c and R_r, see eq. 1) depend on the ROS, an iterative method is necessary to obtain the ROS. So, in order to obtain a formulation which is easier to implement into real time decision making tools, a new version of the Balbi model is developed in order to avoid the use of iterative methods for the calculus of the ROS. This new version is also presented in this IX ICFFR conference. In brief, the main equation (1) is replaced with the following:

$$R = \max(R_b + R_c \; ; \; R_r) \tag{2}$$

Where the component of the ROS due to the flame base radiative heat flux (R_b) is still defined thanks to a Stefan-Boltzman Modelling:

$$R_b = \min\left(\frac{S_t}{\pi}, 1\right)\frac{BT^4}{\beta\rho_v q} \tag{3}$$

And where the two other components are the following:

$$R_c = \min\left(\sqrt{\frac{b\,U}{K}}, b\,U\right) \tag{4}$$

$$R_r = s\,\frac{r_{00}}{u_0}\,(2A-1)(U - U_r) \tag{5}$$

If the drag forces law (*K*) is still a linear function of the packing ratio (β), the modelling of the radiative coefficient (*A*) and the upward gas velocity (u_0) are multiplied by a term τ_b which represents the fuel burning rate:

$$A = \min\left(\frac{S}{2\pi}; 1\right)\frac{\chi_0 \Delta H}{4q}\,\tau_b \tag{6}$$

$$u_0 = 2\,\frac{(s_t+1)}{\tau_0}\,\frac{\rho_v}{\rho_a}\,\frac{T}{T_a}\min(S, 2\pi)\,\tau_b \tag{7}$$

Finally, the convective coefficient *b* is modelled as follows:

$$b = a\,\frac{\Delta H}{q\,\tau_0}\,\sqrt{\frac{s}{\beta}} \tag{8}$$

2.2. Modelling of the fire induced wind

As the flame needs fresh air for the combustion, it is assumed that this fresh air enters into the flame on a given height (denoted by h_a, see fig. 1). So, a simplified mass balance leads to:

$$\rho_a\,h_a\,U = s_t\,L\,\dot{\sigma} \tag{9}$$

After some simplifications, eq. 8 yields the expression of the fire induced wind:

$$U = \frac{R}{p} \tag{10}$$

Where *p* denotes the term:

$$p = h_0\,\frac{h_a\,h\sqrt{\beta}}{s_t\,\tau} \tag{11}$$

When the packing ratio β increases, there is less and less fresh air that could enter the flame base and then the given height h_a needs to increase. Thus, it is assumed that the given height is proportional to the square root of the packing ratio and the fuel height (*h*):

$$h_a = h_0\,h\,\sqrt{\beta} \tag{12}$$

Where h_0 is a scaling factor.

Finally, using eq. 12, the coefficient *p* is defined as follows:

$$p = h_0\,\frac{\rho_a}{\rho_v}\,\frac{1}{\sqrt{\beta}} \tag{13}$$

This modelling is possible thanks to the new formulation of the Balbi model whose main equation is defined by eq. (2).

2.3. The coupled model

Note that under zero wind conditions or when the ambient wind is not strong enough, the external wind *U* in eqs 2—8 is replaced by the fire induced wind.

When the slope angle (α) increases, the induced wind *U* increases as well and then the flame base cools. Consequently, the upward gas velocity u_0 decreases and the flame tilt angle γ increases. It therefore leads to a decrease in the vertical heat losses of the convective flow and to an increasing convective coefficient *b* through the scaling factor a (see eq. 8). From a physical point of view, it means that the free flame F1 flattens the flame F2. So it is assumed that the scaling factor a linearly depends on the terrain slope angle α.

As the combustion rate τ_b decreases, the radiative coefficient A decreases as well and turns smaller than ½. Therefore, the free flame radiation can be neglected and $R_r = 0$. Finally, eq. 2 yields:

$$R = R_b + R_c \tag{14}$$

The expression of the ROS can be expanded according to two different induced wind regimes:

(1) For low induced wind values, $R_c = b\,U$ and using eq. 10:

$$R = R_b + b\,U = R_b + b\,\frac{R}{p} \tag{15}$$

Eq. 15 allows the characterisation of the ROS R:

$$R = \frac{R_b}{1-\frac{b}{p}} = \frac{R_b}{1-\frac{\alpha}{\alpha_\infty}} \tag{16}$$

Where α_∞ is a critical slope angle related to some fuel characteristics and model parameters:

$$\alpha_\infty = h_0\,\frac{\rho_a}{\rho_v}\,\frac{1}{\sqrt{s}}\,\frac{q\,\tau_0}{a_0\,\Delta H} \tag{17}$$

(2) For high induced wind values,

$$R = R_b + \sqrt{\frac{b\,U}{K}} = R_b + \sqrt{\frac{b}{p}\,\frac{R}{K}} \tag{18}$$

After some calculations, eq. 18 yields:

$$R = \frac{\alpha}{\alpha_\infty\,K} \tag{19}$$

The final expression of the ROS is obtained in merging eqs. 16 and 19:

$$R = \begin{cases} \frac{R_b}{1-\frac{\alpha}{\alpha_\infty}} \; if\ \alpha < \alpha_\infty \\ \frac{\alpha}{\alpha_\infty\,K} \; if\ \alpha \geq \alpha_\infty \end{cases} \tag{20}$$

3. Numerical results and discussion

The model given by eq. 20 is tested against three sets of laboratory experiments conducted under zero-wind conditions. The set of experiments conducted by Butler *et al*. (2007) aims at studying the fire spread on slope. An excelsior fuel bed with three different heights (and packing ratios) and six different slope angles ranging from -17° to 43° were set. The second set of experiments was performed by Liu *et al*. (2014). Fires spreading on 10 different values of the slope angle (from 0 to 32°) across a dead pine needles fuel bed were monitored. The last set of laboratory experiments carried out with the same pine needles fuel bed is composed of four series of fires spreading upslope (slope angle ranging from 0 to 40°). Each series differs from another by the dimensions (the height) of the lateral walls of the bench.

All the ROS measurements in the three sets of experiments suggest two different types of fire behaviour. Up to a specific value of the slope angle (which is different from one experiment to another), the fire growths slowly with a very low to moderate ROS. Beyond this threshold value, a dramatic acceleration of the ROS is observed.

The numerical results obtained by the proposed model against the experiments performed by Butler *et al.* (2007), and by Liu *et al.* (2014, 2022) are plotted in figs. 2 and 3, respectively. Note that Butler and his co-authors (2007) calculated the normalized ROS (ratio between ROS and ROS0, obtained for zero-wind and zero-slope) in all their set of experiments.

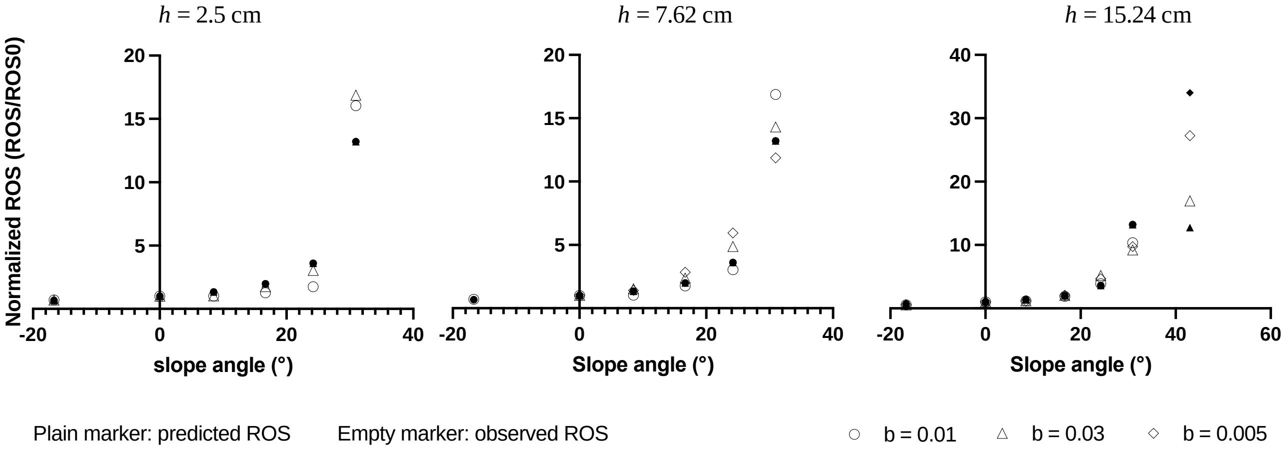

Figure 2 – Comparison between observed ROS (empty markers) and predicted ROS (plain markers) for three different fuel heights (2.5, 7.62 and 15.24 cm) and three different packing ratios (0.01, 0.03 and 0.005) in the set of experiments carried out by Butler et al. (2007)

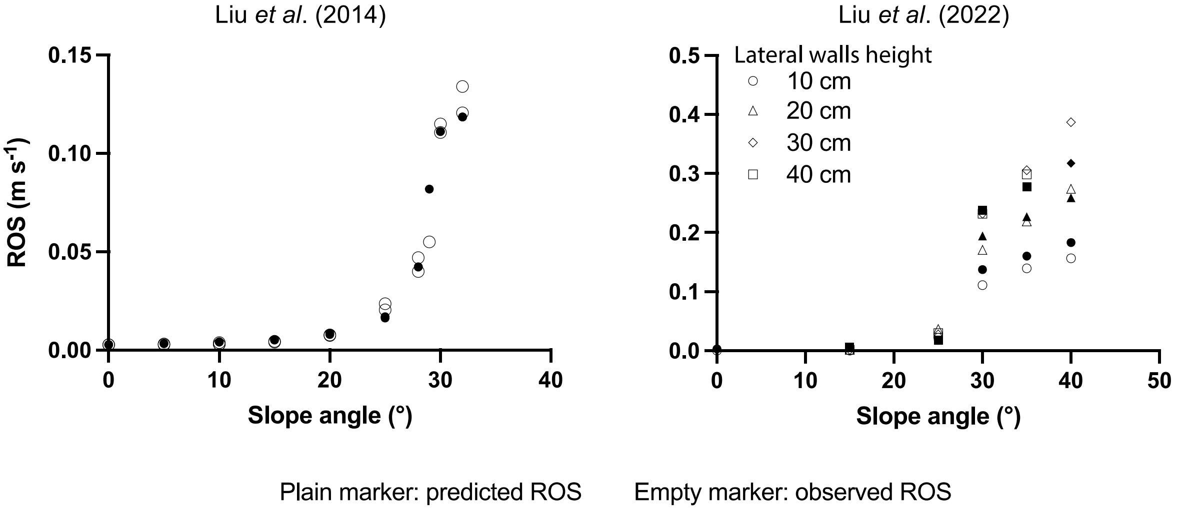

Figure 3 – Comparison between predicted ROS (plain markers) and observed ROS (empty markers) in the set of fire experiments conducted by Liu et al. (2014) (left plot) and by Liu et al. (2022) (right plot). Liu et al. (2022) measured several propagations with only a change in the height of the lateral walls of their experimental bench.

The agreement between observed and predicted rate of spread is assessed using three statistical tools whose results are presented in table 1. Both Normalized Mean Square Error (NMSE) and Mean Absolute Percentage Error (MAPE) are useful for estimating the overall deviations and the Fractional Bias (FB) allows to understand if a model shows under-predictions or over-predictions. An ideal model is obtained for a zero NMSE, MAPE and FB.

Table 1- Agreement between observed and predicted rate of spread estimated with three statistical tools (NMSE, Normalized Mean Square Error, MAPE, Mean Absolute Percentage Error and FB, Fractional Bias)

Set of experiments	*NMSE*	*MAPE*	*FB*
Butler *et al*. (2007)	0.25	18%	0.08
Liu *et al*. (2014)	0.04	16%	0.07
Liu *et al*. (2022)	0.02	58%	0.29
Winter high intensity fire (unpublished)	0.03	20%	0.18

According to figs. 2 and 3, the ROS predicted by the proposed model seems to match well the trends of the ROS against slope angle. The slow increasing of the ROS for small values of the slope angle and the ROS acceleration are correctly reproduced. This visual impression is confirmed by the error results (table 1) with low NMSE and MAPE, except for the last set of laboratory experiments. Indeed, 58% is a quite high value for the MAPE but this result is mainly due to the two first values (where the slope angle is equal to 0° and 15°) with a practically zero ROS (order of magnitude smaller than a millimetre per second). If these two first values are removed from the calculation, the MAPE falls to a value of 17%.

The model has also been tested against an experimental shrubland fire conducted in the north-western of Corsica in march, 2021. The plot was approximately 150 m (length) x 30 m (width) and was burnt on a steep sloped terrain (slope angle ~ 28°) upon winter environmental conditions (ambient temperature ~ 6°C, weak wind velocity ~ 1.3 m s^{-1}). This fire fell into the very high fire severity (Cheney, 1981) with a fireline intensity close to 10 MW m^{-1} and a very fast ROS (0.45 m s^{-1}). As the Balbi model (Chatelon *et al.* 2022) does not include any fire induced wind sub-model, it provides poor results with a predicted ROS equal to 0.1 m s^{-1}. The ROS calculated with the proposed induced wind model (eq. 20) is equal to 0.54 m s^{-1} and is clearly a good approximation of the observed ROS. Indeed table 1 provides small errors (NMSE = 0.03 and MAPE = 20%).

The three sets of laboratory experiments exhibit the same ROS behaviour, consisting in a very slow increase of the ROS up to a threshold value of the terrain slope angle. Below this threshold value, without external wind, the fire spreads as on flat terrain, where the main heat transfer mechanism is the radiation from the fuel burning particles area. Beyond this value, the ROS highly accelerates in an exponential way for Liu *et al.* (2014) and Butler *et al.* (2007) or in a quite linear way in the experiments carried out by Liu *et al.* (2022). The slope angle threshold value seems to be different for each fire experiments series but approximately ranges from 20° to 30°. For these steep slopes, the flame is more tilted on the ground and creates a convective airflow in order to compensate the draft caused by the hot gases moving upwards. This feedback accelerates the ROS and in certain cases, an equilibrium is not obtained, causing a fire eruption. The proposed model (eq. 20) suggests two different behaviours splitted by a threshold slope angle calculated with the model. The numerical results shows a quite good agreement for these sets of laboratory experiments and for the winter fire at the field scale.

4. Conclusion

An accurate modelling of the convective flow induced by a fire spreading on a steep sloped terrain is the first step towards the modelling of eruptive fires. This work is a first attempt to give a physical formulation to this fire induced wind phenomenon. If the tests against three sets of laboratory experiments and against a field scale shrubland fire are very encouraging (with quite small deviations), the proposed model needs to be confronted to much more laboratory and field experiments in order to improve the physical formulation.

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