Upslope Fire and Eruptive Fires

F.J. Chatelon, **J.H. Balbi**, **J.L. Rossi**, and **T. Marcelli**, University of Corsica, Corte, Corsica, France

Abstract—This work deals with a fire spreading upslope under either no-wind conditions or weak wind velocities. The surface fire propagation model developed at the University of Corsica is used; this model takes into account convective and radiative effects. The model is based on the coupling of the properties of the spreading fire with other conditions (wind, topography) and consists of a feedback effect caused by the flow induced by the fire in the presence of a positive slope. The expression of this induced wind, coupled to the propagation model gives an algebraic relationship for the rate of spread (ROS) which depends on the terrain slope angle. For operational matters, the main goal consists in obtaining very simple conditions necessary to eruption triggering. A simplification of the ROS relationship leads to a triggering condition which only depends on fuel characteristics and the threshold slope angle.

Keywords: steady-state model, rate of spread, fire eruption, convective flow, induced wind.

INTRODUCTION

Eruptive fires are characterized by a sudden and unpredictable acceleration of the ROS, even under low wind speeds or small slope angle conditions. So eruptive fires are extremely dangerous for firefighters and they are the cause of several human losses.

In the literature, there are some empirical models that describe fire behavior during such eruptions (Dold et al. 2011; Viegas 2006), but to our knowledge, none of them are able to predict the eruption's onset.

The main question regards the explanation of the phenomenon. Among several explanations found in the literature, we considered the pioneering interpretation proposed by Viegas (2004a), because it has never been refuted by an example of eruptive fire accident. It consists of a feedback effect caused by the convective flow induced by the fire to compensate for the draft caused by the hot gases moving upwards. This induced wind was proved with laboratory experiments (Viegas and Pita 2004) and was observed at the field scale in the Gestosa fire experiments (Viegas and Pita 2004), and also measured in the Freixo accident (Viegas 2004b).

Thanks to a simplified mass balance, a physical modeling of the convective induced wind is coupled to the radiative physical propagation model developed at the University of Corsica. The coupling of the induced wind modeling and the surface fire propagation model gives an analytical condition of danger (Balbi et al., 2014). As long as this relationship is satisfied, a fire cannot erupt. But when the relationship is no longer satisfied, eruption is possible, but it is not assured. Then it depends on the value of the terrain slope angle. Unfortunately, it is not possible to find an analytical condition which gives the threshold value from which eruption is sure. We have to solve the model numerically.

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THE RADIATIVE-CONVECTIVE SIMPLIFIED PHYSICAL MODEL

The previous condition of danger (Balbi et al. 2014) has been established thanks to the radiative-only simplified physical model developed at the University of Corsica.

ROS With External Wind

This year, the fire modeling team of the University of Corsica elaborated a radiative-convective simplified physical model without any model parameters. The ROS is defined as the sum of three contributions: radiation from the flame base R_b (fuel burning particles area), flame radiation R_f and convection R_c (Balbi et al., 2018).

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

The ROS is an increasing function of the wind speed (see fig. 1). After a fast increase, the ROS reaches a plateau which is obtained for a threshold value of the wind speed. The ROS curve could be approximated by three segments (see fig. 1). As the analytical expressions of these three segments are known, it is easy to find the values of $R_{c\infty}$, U_c, and p_∞. Note that (fig. 1) pc is the slope of the straight line which pass through the two points (0,0) and (U_c, $R_{c\infty}$).

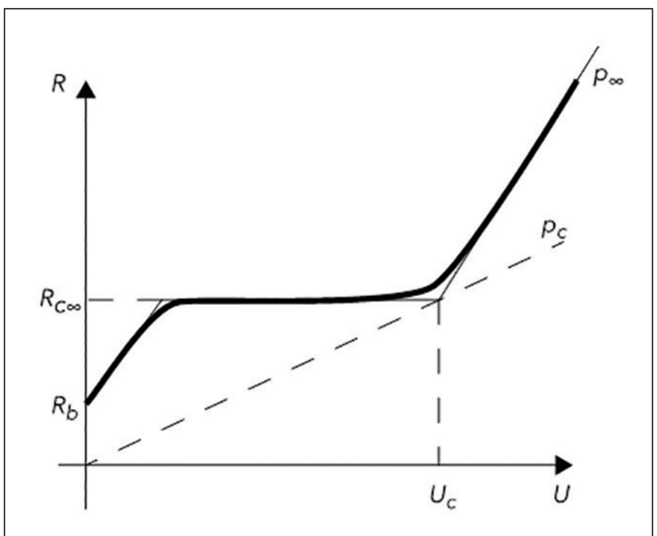

Figure 1—A qualitative illustration of the rate of spread given by equation 1 of the Balbi model.

Convective Flow Induced by the Fire, i.e. 'Induced Wind'

A fire eruption may occur when the external wind is weak or under no wind conditions with a slope. In this case, the fire creates an induced airflow in order to compensate for the draft caused by the hot gases moving upwards. A physical modeling of this "induced wind" is obtained by setting a stoichiometric coefficient st (air/pyrolysis gases):

$$\rho_a \, h \, U = s_t \, L \, \dot{\sigma} \tag{2}$$

where ρ_a is the air density, h is the fuel thickness, U is the normal component of the wind speed, L is the flame depth and $\dot{\sigma}$ is the mass loss rate.

After some calculations, we obtain the following expression of the rate of spread:

$$R = p\, U \tag{3}$$

Equation (3) is a linear function of the wind speed and p is its slope.

Fire Behavior

The solution of the two coupled equations (1) and (3) is the intersection of the straight line given by (3) and the increasing function given by (1). Two different cases may occur:

First case: $p > p_c$

We begin with no wind ($U = 0$) and rate of spread equal to R_b. We can see in figure 2 (left) that induced wind involves the next value U_1 of the wind speed which then gives the new rate of spread R_1. By following, the coupled system (1, 3) leads to a stable solution (U_∞, $R_{c\infty}$) which is a steady state solution and the fire cannot erupt.

Second case: $p < p_c$

With the same process, we can observe on figure 2 (right) that the fixed-point method diverges. So, the regime is an unsteady one and eruption is sure.

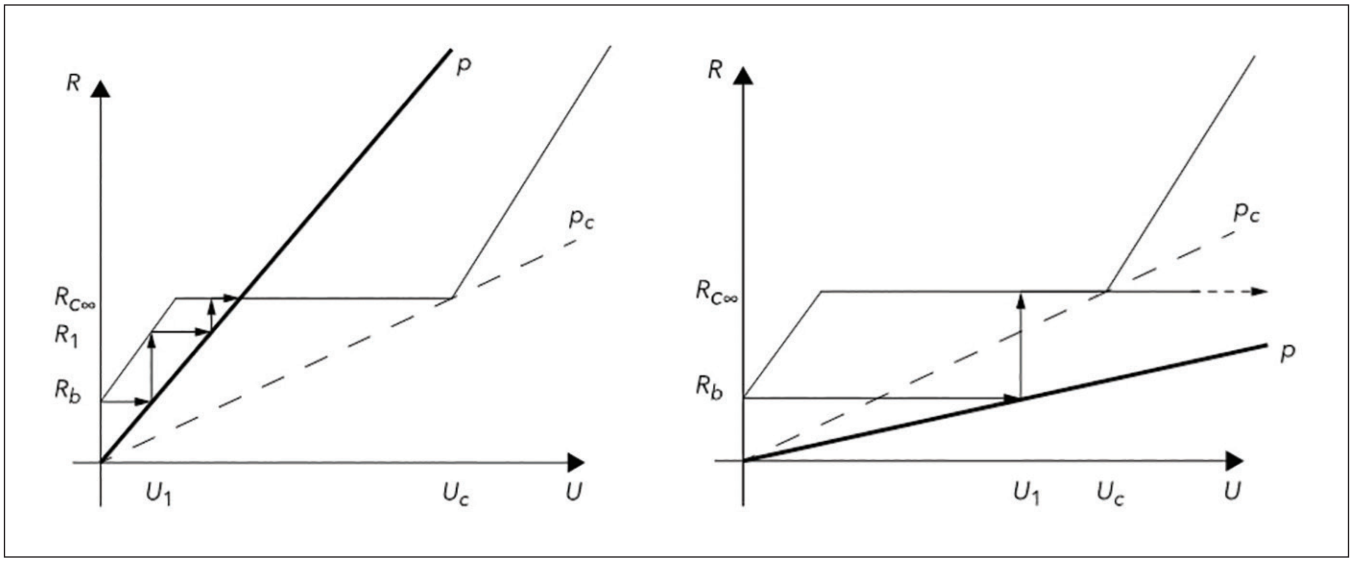

Figure 2—A qualitative illustration of the rate of spread given by equation 1 of the Balbi model and equation 3 obtained with a physical modeling of induced wind (with $p > p_c$ on the left and $p < p_c$ on the right).

Eruptive Conditions

The threshold value is obtained when $p = p_c$. This condition leads to an analytical value of the threshold terrain slope angle denoted by α_{th} which depends on fuel characteristics and fire front width in the following manner:

$$\tan \alpha_{th} = \frac{A}{2A-1} + 10^4 \left(\frac{\Delta H}{\rho \tau_0 K u_{00}}\right)^{\frac{1}{2}} \frac{1}{s\beta}\left(\frac{4}{2A-1} - \frac{s\beta}{\upsilon}\right) \quad (4)$$

where A is a radiant coefficient which depends on fuel characteristics and on fire dynamics properties (fire front width and flame length), ΔH is the heat of combustion of the pyrolysis gases, ρ is the fuel density, K is a drag forces coefficient, s is the surface area to volume ratio, β is the packing ratio, ν is the fuel absorption coefficient, τ_0 is the Anderson's model residence time coefficient and u_{00} is a coefficient of the upward gas velocity.

CONCLUSION

In conclusion, we can say that according to our model, all the situations favorable to a fire eruption are those in which the fire front width remains important. Obviously canyons have very dangerous geometries; the famaliçao accident or the laboratory experiments conducted by Viegas and Pita (2004) are other examples. Finally, as it was proved by Sharples et al. 2010 and Dold and Zinoviev 2009, trenches or corridors are very dangerous situations.

In this work, we presented a steady state propagation model only designed to predict the eruption's onset. If we want to know the behavior of the ROS during the eruption, we have to use the unsteady version of the propagation model because a fire eruption is obviously an unsteady phenomenon. We can find the threshold slope angle from which eruption will occur but in fact, thanks to a very fast code, we are able to find the value of any of the parameters involved in the model which can cause an eruption.

We are not able to take into account a heterogeneous vegetation (but this limitation can be solved using an equivalent fuel model) or eruptive crown fires because the propagation model is only designed for surface fires.

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