On the existence of a steady state regime for slope and wind driven fires

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Abstract. Forest fire behaviour analysis and prediction is based on the assumption that for a given set of boundary conditions a steady-state of fire propagation exists with a well-defined rate of spread. The evolution of a fire front for linear and point ignited fires is analysed and it is shown that, even in nominally uniform and permanent conditions, the rate of spread of the head fire does not remain constant in the general case of slope- and wind-driven fires due to joint convection and radiation effects. The basic case of a linear fire front without slope and without wind is one of the few cases for which the rate of spread is well defined and remains constant. If there is slope or wind in point ignition fires, the rate of spread of the head fire tends to increase while for linear ignition fires the contrary happens. It is shown that convective effects induced by the fire for steep slope terrain can produce the so-called ‘blow-up’ effect even in the absence of any other special atmospheric conditions. Therefore the definition of rate of spread of a fire and its evaluation from laboratory and field experiments is strongly questioned.

Additional keywords: fire behaviour; modelling; slope and wind effects; fire dynamics; fire growth; fire acceleration; convective effects; ‘blow-up’; canyon fires.

Introduction

Forest fire behaviour analysis and modelling is currently based on the concept of a rate of spread of fire front advance, normally designated rate of spread. It is commonly assumed that, for a given fuel bed, under uniform and permanent ambient boundary conditions there is a well-defined and unique value of the rate of spread. The evaluation of this rate of spread value is indeed the objective of most fire behaviour prediction models. A very well known example is the Rothermel model (Rothermel 1972) for which, given a set of fuel bed properties and ambient conditions (characteristic slope and wind values), the rate of spread value \( R \) is obtained as an output. The same applies to other physical, semi-empirical or empirical models. For example laboratory simulations try to create such well-defined and permanent ambient conditions.

Implicit or imbedded in the above assumption is the postulation of the existence of a steady-state regime for fire spread when all the spatially distributed parameters are uniform and the temporally distributed factors are constant (permanent boundary conditions). This problem can be formulated also as that of the existence of a single value for the rate of spread of a fire front under those conditions.

Given the fact that in real fires the above conditions are not met in the large majority of cases, one cannot expect that the fire will achieve a steady-state regime in real life conditions. In the field either fuel bed or topography change from one point to another or wind velocity and direction change with time. Therefore when dealing with real fires or even with fires in the open air a ‘quasi-steady’ state or regime is invoked to model fire behaviour from one time step to another or from one fuel cell to another. By definition this ‘quasi-steady’ evolution assumes that during each time step at a given location of the fire front a steady-state regime exists and that it is well defined. To predict fire spread during that time step one assumes that the parameters that were estimated by some physical or empirical model for the equivalent steady-state regime are applicable. Therefore the problem of existence of the steady-state regime that is addressed in this paper is not at all purely academic but, on the contrary, it has important practical implications.

In practical conditions it is important to recognise that in some cases even when the ambient conditions remain the same, fire behaviour may change dynamically and surprise those who are at the fire line expecting one behaviour and finding another one. Fire dynamics associated to its local shape or to terrain configuration may produce changes in the rate of spread even when the other ambient conditions remain unchanged. Unfortunately many cases in the past confirm this assertion (Chandler et al. 1983; Pyne 1984; Cheney et al. 2001).

In this paper it is shown that in the general situation of wind or slope driven fires the existence of a steady-state regime is not proved. On the contrary it is demonstrated that, even for nominally uniform and permanent boundary conditions like
the ones created in well controlled laboratory experiments, the rate of spread of the fire front evolves with time and depends on the fire evolution history. As a consequence, for this type of fire the evaluation of the rate of spread becomes a much more complex problem.

Cheney and Gould (1995) address the problem of fire growth and the existence of a quasi-steady regime of fire spread. They introduced the concept of potential rate of spread indicating that the same fuel-bed may have a range of values of the rate of spread between zero and the so-called potential rate of spread $R_p$, for a given set of ambient conditions, depending on the ignition pattern and on the effective width of the fire front. They present results obtained in grassland fires on horizontal terrain.

In a Letter to the Editor, Cheney and Gould (1997), the same authors question the indiscriminate use of the terms fire growth and fire acceleration. Based on their observations they note that during fire growth fire may accelerate (increase of the maximum rate of spread) or decelerate. Changing wind may produce this fire acceleration but it was observed that, even in nominally constant wind and other boundary conditions, rate of spread changed with time. These authors relate those modifications to changing convection and radiation effects at the fire front. The concept of fire growth proposed by these authors is adopted here in the sense that since its origin a fire grows (its total burned area increases monotonically). At the same time the rate of spread at given points of the fire perimeter, namely at the head of the fire, may change with time (positive or negative acceleration).

Drysdale (1985) analyses the spread of flame fronts over inclined surfaces in the context of structural fires. He mentions that upward flame spread on a semi-infinite solid can never achieve a steady-state of propagation. In particular the development of a vertical wall fire can be approximated by an exponential law. This is equivalent to an exponential growth of the rate of spread with time.

In compartment fires the phenomenon of ‘flash-over’ is described as a regime of very intense fire spread with extremely high values of energy release (Drysdale 1985). This regime is somewhat equivalent to the ‘blow-up’ that is observed in some forest fires in which extremely high rates of spread are observed.

The author had observed that in a given fuel-bed for a given set of ambient conditions, the rate of spread could be obtained. An example of this was the case of a line fire on a slope that was considered in Viegas (2002). If the fire line is not horizontal, the existence of non-uniform convection flow along the fire front creates different values of the rate of spread and as a result the fire line changes its orientation during its spread. This effect was designated ‘fire line rotation’ and it is indeed the recognition that for a given set of boundary conditions we do not have always a well-defined rate of spread value.

Studies of joint wind and slope effects (Viegas 2001) confirmed these observations. It was concluded that in the general case of non-aligned wind velocity and slope gradient directions, fire growth is not stable: the shape of the fire is always changing and there is not a homothetic shape of the fire perimeter as some modellers assume. Recent experiments made of fire spread in canyon configurations (Viegas and Pita 2002) provide evidence that terrain configuration can modify convection flow around the fire front in such a way that extremely high rates of spread are produced. Even at the relatively small scale of a laboratory combustion table it was possible to observe a sort of ‘blow-up’ of the fire front. In spite of the fact that the boundary conditions were permanent and uniform it was observed that in some cases the rate of spread increased continuously during fire growth.

In the present study the problem of the existence of a constant rate of spread for a fire front spreading in a uniform fuel bed under permanent and uniform boundary conditions is addressed. This problem is of great practical interest both in theoretical and in operational terms. Most fire behaviour models are based on the assumption that such a rate of spread exists and that it can be obtained from mathematical models if the boundary conditions are known. Besides this, all the experimental work is based on the assumption that it is possible to determine fire rate of spread under well controlled conditions.

The author considers the very simple cases of point or line source fires spreading on uniform fuel beds under the effects of uniform wind, uniform slope or terrain concave shape (canyon shape). Rate of spread changes during fire growth observed in laboratory experiments are analysed and conclusions are reached.

Symbols used in the text are described in Table 1.

**Fire front acceleration**

*Definition of steady-state*

In fire behaviour modelling one seeks to predict the evolution of the fire front along the terrain surface as a function of time. Considering the simplified case of a uni-dimensional propagation along a linear direction OX, the position of the fire front at a given time $t$ since fire start is given by:

$$x = \int_0^t R \cdot dt.$$  

If the rate of spread is constant, this integration can be computed with a much simpler equation:

$$x = R \cdot t.$$  

This is the situation that one would expect to have if the fuel bed properties were uniform and the boundary conditions were permanent with time. This is what we define by steady-state propagation.

In real fires spreading for a finite lapse of time, one cannot expect that the rate of spread will remain constant with time,
as it depends on many properties that change along space (fuel bed, topography) and with time (wind direction and intensity). In such cases it is assumed that the time lapse can be broken into appropriate time steps such that a constant rate of spread value can be considered in each step and the evolution of the fire front is then given by:

$$x = \sum_{i=1}^{n} R_i \cdot (t_i - t_{i-1}).$$

Equation (3) corresponds to a quasi-steady-state approach, as it assumes that in each time step $\Delta t_i$ the rate of spread $R_i$ is a constant.

The problem that is now considered is to know if the value of $R_i$ is dependent only on the boundary conditions, as equation (2) assumes, or if it also depends on the time history of fire growth.

In the first case the quasi-steady-state approach is valid and practicable. In the contrary case it becomes very doubtful

### Table 1. Symbols used in the text

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Equation No.</th>
<th>Fig. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Exponent in equation (9)</td>
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<tr>
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<td>Coefficients in linear advance equation</td>
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<tr>
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<td>$B$</td>
<td>Fire front width</td>
<td>m</td>
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<td></td>
</tr>
<tr>
<td>$D$</td>
<td>Flame depth</td>
<td>m</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>$h_t$</td>
<td>Ambient air relative humidity</td>
<td>%</td>
<td>4</td>
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</tr>
<tr>
<td>$H_t$</td>
<td>Fuel bed height</td>
<td>m</td>
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<td>Flame length</td>
<td>m</td>
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<td>$m_f$</td>
<td>Fuel moisture content</td>
<td>%</td>
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<td></td>
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<td>$m$</td>
<td>Mass consumption rate</td>
<td>kg s$^{-1}$</td>
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<td></td>
</tr>
<tr>
<td>$M$</td>
<td>Fuel load</td>
<td>kg m$^{-2}$</td>
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</tr>
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<tr>
<td>$OX'_1Y'_1Z'_1$</td>
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<tr>
<td>$OX'_1Y'_1Z'_1$</td>
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<tr>
<td>$P_i$</td>
<td>Generic point at time step $t_i$</td>
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<td>—</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat release per unit of time and per unit of fire length</td>
<td>J s$^{-1}$ m$^{-1}$</td>
<td>8</td>
<td></td>
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<tr>
<td>$r_1^2$, $r_2^2$</td>
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<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Rate of spread</td>
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<td></td>
</tr>
<tr>
<td>$R_{_R}$</td>
<td>Rate of spread between $t_{i-1}$ and $t_i$</td>
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<td></td>
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<tr>
<td>$R_{<em>R}$, $R</em>{<em>R</em>{med}}$, $R_{<em>R</em>{fin}}$</td>
<td>Initial, average and final rate of spread given by quadratic equation</td>
<td>m s$^{-1}$</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$R_{_R}$, $R_3$</td>
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<td>m s$^{-1}$</td>
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<td></td>
</tr>
<tr>
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<td>Potential rate of spread</td>
<td>m s$^{-1}$</td>
<td>—</td>
<td></td>
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<tr>
<td>$t$</td>
<td>Time</td>
<td>s</td>
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<td></td>
</tr>
<tr>
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<td>Time steps</td>
<td>s</td>
<td>3</td>
<td></td>
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<tr>
<td>$t_{<em>R</em>{TOT}}$</td>
<td>Total duration of test</td>
<td>s</td>
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<td>Ambient air temperature</td>
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<td>$T_{_rad}$</td>
<td>Equivalent radiant temperature</td>
<td>K</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$u_i$</td>
<td>Induced wind velocity</td>
<td>m s$^{-1}$</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>$u_c$</td>
<td>Friction velocity</td>
<td>m s$^{-1}$</td>
<td>—</td>
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<tr>
<td>$U$</td>
<td>Local wind velocity</td>
<td>m s$^{-1}$</td>
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<td>$U_{fl}$</td>
<td>Fundamental flame velocity</td>
<td>m s$^{-1}$</td>
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<td>$U_{_max}$</td>
<td>Maximum wind velocity above which fire is extinguished</td>
<td>m s$^{-1}$</td>
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<td>$U_{_min}$</td>
<td>Minimum wind velocity required to affect combustion reaction</td>
<td>m s$^{-1}$</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$U_0$</td>
<td>Reference wind velocity</td>
<td>m s$^{-1}$</td>
<td>1</td>
<td></td>
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<tr>
<td>$x$</td>
<td>Distance from fire origin</td>
<td>m</td>
<td>1</td>
<td></td>
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<td>$x_1$</td>
<td>Fire advance given by linear equation</td>
<td>m</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$x_2$</td>
<td>Fire advance given by quadratic equation</td>
<td>m</td>
<td>12</td>
<td></td>
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<tr>
<td>$\alpha$</td>
<td>Slope angle</td>
<td>—</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>$\beta$</td>
<td>Fuel bed packing ratio</td>
<td>—</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>Geometrical parameter in a canyon</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time step</td>
<td>s</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Relative change of rate of spread during a test</td>
<td>—</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{f}$</td>
<td>Fraction of available fuel that participates in the propagation phase</td>
<td>—</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>Flame angle in relation to fuel bed surface</td>
<td>—</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fire front radius of curvature</td>
<td>m</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Particle surface to volume ratio</td>
<td>m$^{-1}$</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
if we can predict fire behaviour using present models that ignore the way fire grows. As will be seen the conclusions of
the present study are in favour of the second condition, i.e.
that in the general case the rate of spread of a fire front is
dependent on fire growth history and therefore the explicit
dependence of $R$ on time cannot be ignored.

**Problem formulation**

In this study we shall consider a surface fire with a flaming
front that propagates on a porous fuel bed of constant height
$H_f$. The fuel bed properties are considered to be uniform
and isotropic in statistical terms. The fuel bed is based on
a plane surface that is either horizontal or inclined with a
slope $\alpha$ (Fig. 1). A basic frame of reference $O_XO_YO_Z$ linked
to Earth is shown in the same figure. The horizontal plane
is coincident with $O_XO_Y$. An auxiliary frame $O_X'Y'Z'_1$ is
used to describe fire spread; the surface of the fuel bed is
coincident with $O_XY_1$. A third frame $O'X_1Y_1Z'_1$ linked
to the fire front can be used in order to make the description
of the phenomena in the vicinity of the fire front independent
of time in the case of a constant value of the rate of spread $R$.

The wind field $U(x,y,z)$ above the fuel bed, in the absence
of fire, is assumed to be independent of the horizontal coor-
dinates $(U(z))$. As a consequence a reference wind velocity
value $U_o$ for the flow above the fuel bed can be considered
as uniform in the entire space. This reference velocity can be
either the ‘mid-flame height’ wind velocity, as proposed by
Rothermel (1972), the friction velocity $u_z$, as proposed by
Viegas and Neto (1991), or some other characteristic value.
A particular case that will be analysed is that of the absence
of wind ($U_o = 0$). If the fuel bed is inclined we shall assume
that the wind direction is parallel to the slope gradient (Fig. 1).
In the present study we shall consider either wind or slope but
not both at the same time.

![Fig. 1. Schematic presentation of a linear fire front in a uniform fuel bed with a constant slope or with a uniform wind flow.](image)

In this article analysis is restricted mainly to head fires
and to plane fuel beds. Extension to other sectors of the fire
front—like the flanks or the rear—is quite straightforward.
Later a mention is made of a fire on the non-planar config-
uration of a canyon; it is shown that the concave shape of
that configuration has a very important effect in enhancing
fire induced convection and therefore in modifying its rate of
spread (Viegas and Pita 2002).

Convective effects induced by either wind or slope on the
fire front can be treated as being similar for practical effects. It
should be noticed that, although the effects of wind and slope
are analogous or similar, they are not equivalent, as there exist
some differences between the forced convection induced by
wind and the natural convection induced by buoyancy near
the fire front. For convenience we shall deal with these effects
separately whenever justified.

The rate of spread $R$ of a given section of the fire front will
be a function of the following properties (Rothermel 1972):

$$ R = R[Fuel~bed\ (\sigma, M_c, m_f, \beta, H_i, \ldots), T_a, h_f, \rho, \alpha, U]. \quad (4) $$

In this equation the fuel bed properties are designated basic-
ally by the same symbols that are used in Rothermel (1972).
The symbol $\rho$ designates the radius of curvature of the fire
front at the designated point (Fig. 4). Without loss of generality
it is assumed that we are interested in analysing the effects
of terrain slope or wind velocity and fire front curvature for a
given fuel bed and for a particular set of ambient conditions
($T_a$ and $h_f$). In this case we can exclude the corresponding
parameters from equation (1) and write it in the simplified
form for a given fuel bed:

$$ R = R(\rho, \alpha, U). \quad (5) $$

Later we shall generalise this law for other fuels including in it
a reference value $R_o$ that is the basic rate of spread of a linear
fire front ($\rho = \infty$) on a horizontal fuel bed ($\alpha = 0^\circ$) in the
absence of wind ($U_o = 0$) for the same ambient and fuel bed
properties. It is assumed that this property $R_o$ incorporates
the specific influence of all the parameters that appear in
equation (4) but were excluded from equation (5).

In the case of a linear fire front $\rho = \infty$, equation (5) is
reduced to:

$$ R = R(\alpha, U). \quad (6) $$

The propagation of the fire front is the result of an equilibrium
or balance between the following three processes:

1. The heat source, consisting of the chemical exothermic
reaction of combustion of the fuel both in the solid and
in the gaseous phases;
2. The heat transfer, mainly by radiation and convection
from the heat source to the environment and to the
unburned fuel; and
3. The heat sink, consisting mainly of the increase of
enthalpy of the fuel bed particles in the vicinity of the
reaction zone until they reach ignition state.
The spread of the fire front depends on the equilibrium between the propagating flux produced by the heat source and transferred to the heat sink and the amount of energy that is required to ignite the portion of the fuel bed that is in the immediate vicinity of the heat source. It is currently assumed that these two quantities come into a well-defined equilibrium resulting in a precise value of the rate of spread.

We must have in mind that the forest fuel bed is a reactive system; it does not act as a passive agent. On the contrary if it receives more heat a larger part of it will react and will release more heat and the process feeds itself. Therefore the existence of a static equilibrium cannot be assumed as given.

Practically all models assume that under the above conditions the heat source or reaction zone has a well-defined set of geometrical and thermal properties. In particular it is assumed that it consists of a reaction zone or ignition front inside the fuel bed and of a flame front above the fuel bed.

Given the very high temperatures in the gaseous phase of the combustion zone, in the majority of cases it is considered that the heat transfer process is dominated by radiation from the flame. Therefore in all models great care is taken to determine the geometry and the radiometric properties of the flame with great accuracy. In the simpler cases the flame front is represented by a plane surface of length $L$, a width $B$ and inclination $\theta$ in relation to the fuel bed surface (Fig. 2), with an equivalent radiometric temperature $T_{\text{rad}}$. For down-slope or for contrary-wind fires the dominating radiation effect is that of the reaction zone inside the fuel bed, and the flame plays a relatively minor role.

Most models ignore the effect of convection induced by the fire itself. Some models consider that it consists mainly in the cooling of the particles ahead of the fire front due to air entrainment by the fire. The effect of the convective flow due to wind or induced by the fire on the chemical reaction is generally overlooked.

![Fig. 2. Schematic view of a section of a fire line of infinite width on a horizontal fuel bed with favourable wind.](image)

If the values of $L$ or $B$ are large and $\theta$ is small—as is the case for steep slopes or strong wind driven fires—the radiation and convection on the particles ahead of the fire front will pre-heat them and the condition of uniformity on the fuel bed properties along the OX-axis will not be respected in a relatively deep zone near the fire front.

The existence of a steady-state regime requires that a balance or equilibrium among the processes described above exists and that there are no changes in any of those processes. It is also necessary that any fluctuations or small changes of some influencing parameter do not affect the equilibrium state that may have been established.

An important property of the fuel bed particles is their residence time $t_{fr}$, associated with the duration of flaming combustion. The depth of the flame $D$ is approximately:

$$D = R \cdot t_{fr}.$$  \hfill (7)

The extension (depth) of the combustion zone will depend on the availability of oxygen provided by ambient air. It is well known that for an efficient combustion it is required that the ratio between combustive gases and oxygen remains close to the stoichiometric ratio and always inside a given range. It is also understandable that a larger quantity of oxygen will correspond to a wider mass of fuel reacting or burning in a given period of time.

Assuming that a fraction $\varepsilon_f$ of the total fuel load per unit area $M_c$ is consumed during the flaming phase of fire front advance, it is easy to see that the mass loss ratio in the fuel bed and consequently the heat release per unit of fire front width and time will be approximately:

$$Q \propto \dot{m} \propto \varepsilon_f M_c D \cdot R \approx \varepsilon_f M_c t_{fr} \cdot R^2.$$ \hfill (8)

The value of the exponent $a$ in equation (9) is in the range between 0.4 and 0.66 (André et al. 1992).

In the present analysis we are not interested in finding the exact relationship between the parameters involved; the emphasis is to point out the existence of such a relationship in order to put in evidence the feed-back effect between the heat source and the heat sink. Convection near the fire front plays a major role in this effect so it is now analysed in greater detail.

### Convection effects

Let us consider a linear fire front on a horizontal fuel bed with wind. The case of slope can be treated in a similar way given the analogy between both effects.

#### The no-wind case

Let us start with the simple case of no wind conditions that is called the basic case. Usually in this case it is considered that the flame is vertical and therefore $\theta = 90^\circ$. Let us look...
in more detail at the conditions that exist on both sides of the fire front.

The very high temperatures inside the flame cause a drastic reduction of the gas density and therefore a vertical movement of the gases of combustion is produced above the reaction zone. This vertical movement entrains air from the surroundings that becomes mixed with the gaseous fuels and with the products of combustion, forming a thermal plume. For obvious reasons the movement of the flow inside the plume near the ground is horizontal. We can therefore define a reference velocity $u_i$ that is characteristic of the flow induced by buoyancy. From what was said above we conclude that this induced velocity exists near the fire front even if the ambient air is nominally static ($U_0 = 0$). The convective flow inside the fuel bed will depend very much on its porosity.

If the width of the thermal plume is finite there will be a surface that divides on average the flow into two regions of horizontal flow oriented towards this surface. For simplicity we call this surface the ‘symmetry plane’ of the linear plume although this surface is not necessarily a plane.

As the air above the already burned vegetation has a much higher temperature than that near the unburned fuel, it is easy to recognise that the boundary conditions for the flame are not symmetric. In spite of the intensity of the buoyancy forces above the flaming zone the contribution given by the already burned area will induce a displacement of the symmetry plane towards the already burned area or at least a deflection of this plane towards the already burned fuel (Cheney and Gould 1997). Consequently the flame will be inclined backwards $\theta > 90^\circ$ as is shown in Fig. 3.

The negative inclination of the flame front induces a relatively small view factor for the flame and therefore the radiation from the flame does not play a major role in fire spread in this case. For example the view factor of a flame with $\theta = 30^\circ$ is five times greater than the corresponding value for the same flame inclined backwards with $\theta = 150^\circ$ (Vaz 2001). The major contribution comes from the reaction zone inside the fuel bed and, as this zone is not much affected by external factors, we can expect that a steady-state of equilibrium will be achieved in this situation and therefore a well defined rate of spread $R_o$ can be determined. Given the relevance of this rate of spread for no-wind and no-slope conditions, we designate it the basic rate of spread. We shall use it as a reference value that is an intrinsic property of the fuel bed, as it incorporates all the parameters that characterise the fuel bed.

In the previous discussion we considered a linear fire front with a very large width $B$, in the limit close to infinity. In practice it is required that the width of the fire front is much larger than the flame length $B \gg L$ in order to minimise edge effects. These conditions can be fairly achieved for linear fire fronts if the fuel bed width is greater than 5–8 times the flame length (Wotton et al. 1999). For point ignition fires if the radius of curvature $\rho \gg L$, similar conditions can be achieved as well, although this may require a larger space to perform the test (Fig. 4).

**Backward spread**

If wind is blowing in the opposite direction of fire front advance then the flame front will be tilted even more towards the already burned fuel and therefore the value of $\theta$ is increased (cf. Fig. 5).
This mechanism is such that the process feeds on itself and the rate of spread remains practically constant for contrary wind in a given range of wind velocities.

Depending on the porosity of the fuel bed, the flow of air inside the fuel bed will increase and therefore more oxygen will be available for combustion. As a consequence above a certain threshold value \( U_{\min} \) of the wind velocity the flame depth may increase. In this case the rate of spread of the fire front will increase as well.

It is understandable that above a second threshold \( U_{\max} \) the air velocity in the vicinity of the reaction zone may be greater than the fundamental flame velocity \( U_{fl} \) and in this case the flame will be extinguished. This will happen if no other mechanism of fire spread such as spot fires occur. The author observed fire extinction due to contrary winds both in laboratory and in field experiments when either wind velocity or fuel moisture content was very high.

The application of the above description for the down slope fire front is quite straightforward.

### Forward spread

If wind is blowing in the same direction as the fire front advance, then the flame front will be tilted towards the unburned fuel and therefore the value of \( \theta \) is decreased (cf. Fig. 6). Under these conditions the heat transfer from the heat source to the heat sink is greatly enhanced and the rate of spread is increased.

The positive effect of wind will modify the reaction zone that will be much deeper and therefore the induced velocity \( u_I \) will increase as well compared to the no-wind condition. This mechanism is such that the process feeds on itself and the fire front may not reach an equilibrium state. If this happens a condition for which the rate of spread will increase continuously can be produced. This situation is described in the literature as a fire ‘blow-up’ condition and it is very often related to loss of control and also to fatal accidents occurring in forest fires.

There must be some physical limit for the fire acceleration process as the rate of spread cannot increase indefinitely. If no other fire spread mechanisms such as spotting or crowning are present, the limiting value of the fundamental flame velocity \( U_{fl} \) as a threshold for air velocity is applicable also in this case, in spite of the much greater complexity of the turbulent flow inside the reaction zone. If this upper limit exists then it will be certainly correspond to an equilibrium state as there must exist some contrary effect that balances the tendency for the rate of spread to increase indefinitely.

This limiting value of the rate of spread is certainly the same as was designated as potential rate of spread by Cheney and Gould (1995). As was remarked by those authors the \( R_p \) is attained after a transitory period of fire growth that even for very light fuels like herbaceous vegetation may take some minutes. From this we can conclude that the true \( R_p \) for some fuels will be very difficult to reach, as there may not be sufficient time to reach it. Situations in which ‘blow-up’ occurs are among those in which these very high values of the rate of spread can be observed.

A fire front spreading upslope has a similar behaviour to a wind-driven fire. In particular it is observed that, above a certain value of the terrain slope or curvature, the ‘blow-up’ effect can occur. In this case the rate of spread of the fire front can reach the limiting value \( R_p \) that was mentioned before. An open question at present is that of knowing if this limiting value is the same as for a purely wind-driven fire. Intuitively one would expect that this value is an intrinsic property of the fuel bed.

The problem of rate of spread increase with terrain slope is dealt with also in the literature on structural fires. A particularly interesting case is that of a fire spreading on a vertical wall. The analogy of this case in forest fires is that of a fire spreading vertically from the ground along a tree trunk or from one fuel bed layer to another. As the vegetation-covered terrain slope angle is never close to 90°, the analogy between structural fires and forest fires must be made with care.

In Drysdale (1985) it is mentioned that a flaming fire spreading along a vertical wall has a rate of spread that increases exponentially with time. We shall see later that, in porous fuel-beds like those encountered in forests, a similar behaviour can be observed in some circumstances, for slope angles much below 90°.

### Fire front shape

The shape of the fire front influences the rate of spread at its various sections. In the previous discussion we considered a linear fire front with an infinite width \( (B \gg L) \) as shown in Fig. 2. If the front is curved or has a finite width, radiation and convection from the reaction zone to the unburned fuel will not be the same along the fire front. As a consequence the rate of spread will not be uniform along the fire front and some sections of the fire front will advance faster than others. For practical purposes the rate of advance of the head...
of the fire—which corresponds to the local maximum rate of advance—is the one that is more relevant in fire behaviour predictions. In the following discussion we shall consider mainly the head fire rate of spread.

**Finite width**

In experimental fires, both in the field and in the laboratory, quite often the width of the fuel bed is not much larger than the flame length $B/L \neq \infty$ (Fig. 7a). In this case the heat flux to the unburned fuel is not uniform along a line parallel to the fire front. Radiation flux will be stronger near the centre of the fire due to the finite width of the fire front. As a consequence the fire will advance faster in the middle than at its edges (Fig. 7b). The curvature $\rho$ of the head fire—at the centre of the fire front—will decrease and the rate of spread will decrease continuously (Weber 1989).

If there is wind or slope perpendicular to the fire front, this effect may be more pronounced and the rate of spread will decrease with time.

**Point ignition**

In a point ignition fire (Fig. 7c) without wind or slope the shape of the fire front will be a circle with a constant radius. After an initial phase the rate of spread will stabilise or even decrease due to convective effects. The curvature of the fire front will decrease continuously but the convection induced by the already burned area may compensate or even overcome the relative increase of radiation flux. The rate of spread may either increase or decrease during fire growth.

In slope or wind driven fires the curvature of the fire front will produce a rate of spread much smaller than for the corresponding linear fire front. With fire growth the radius of curvature at the head of the fire will increase continuously and the rate of spread will increase. This effect is the contrary to what is observed for a linear fire front, which has a decrease of its curvature and consequently a reduction in its rate of spread during fire growth.

We can conclude that in the case of absence of wind (or slope), a point ignition fire will have a practically constant rate
of spread. The same will happen in the presence of moderate wind (or slope).

**Methodology**

*Experimental set-up*

In order to test the concepts described above we require experimental data. These can be obtained from three sources: (i) real fires; (ii) experimental fires in the field, or (iii) experimental fires in the laboratory. In the first two cases there is no control of ambient conditions and even if these are carefully monitored it is not easy to avoid disturbances caused by fuel bed or topography heterogeneities or by changes in the wind field.

Laboratory experiments have a limitation of scale due to the reduced space that is normally available to perform these experiments, but on the other hand they have the advantage of allowing a careful control of the relevant parameters and allow us to study their influence in a systematic way. In particular a closed laboratory is the only place where either wind or slope can be analysed separately in a systematic way. Besides this we must recognise that an important part of forest fire research—Rothermel (1972)—is actually based on laboratory tests.

In field experiments or in real fires, situations are in general more complex due to the simultaneous influence of many factors. In general the scale of the fire is much larger than in laboratory experiments and quite often the width of the fire front is much larger than the flame length. In spite of these differences similar behaviour can be expected between field and laboratory fire spread, namely in terms of the non-existence of a steady-state for slope or wind driven fires.

The results obtained in a series of laboratory experiments carried out during the past years at the Forest Fire Laboratory of the University of Coimbra shall be used in this work. These experiments were performed by several researchers with the purpose of studying wind and slope driven fires under the supervision of the author. As will be described later, in each experiment a rate of spread was determined by measuring the time the fire took to burn a set of strings that were placed at equal distances across the fuel bed. A linear fit was adjusted to the plot of distance v. time obtained in each test. As the correlation coefficient was usually above 0.96 it was assumed that a constant rate of spread existed in each case. These data were now re-analysed more carefully and it was found that the hypothesis of linear fit is not correct in most cases as will be shown.

The tests reported here were selected from several hundreds of results existing on file at our Fire Laboratory and no experiments were made on purpose for the present study. Although many more experiments were analysed, some of those that formed a complete set of data were chosen. The results presented here have the same trends as those from the other experiments that were analysed and are not shown.

The experiments were carried out in three burn tables that are briefly described below.

*Combustion Tunnel TC 2*

This Combustion Tunnel was described in Viegas et al. (1998). It has a horizontal table area of 3 m × 8 m and vertical walls with a height of 2 m along its sides and it is open on the top (no ceiling) and at its down-wind end. Wind of constant velocity \(0 < U_0 < 8 \text{ m s}^{-1}\) can be produced by two axial fans of variable rotational velocity. A flow straightener formed by square-section ducts and a settling chamber was employed to suppress the rotation induced by the fans and to make the flow more uniform at the entrance of the working section. The flow field in the working chamber was measured using pitot tubes and other velocity sensors to check its uniformity. It was found that outside the boundary layer the flow velocity can be characterised by a single value of \(U_0\) with an error \(±0.5 \text{ m s}^{-1}\). The frequency of rotational velocity \(f(\text{Hz})\) is linearly related to the reference wind velocity \(U_0\) (m s\(^{-1}\)) in the Combustion Tunnel. The fuel bed was prepared starting at a distance of 1 m from the table's leading edge and leaving a distance of around 0.5 m from the walls; therefore the useful area was usually of 2 m × 6 m. These experiments were carried out in February 2001.

*Inclination Table DV2*

The Inclination Table was already described in Viegas et al. (1998, 2002). This table has a metallic structure with a surface of 4 m × 4 m with a useful area of 3 m × 3 m that can be inclined at any desired angle \(\alpha\) between \(0^\circ\) and \(40^\circ\). The inclination of the table is achieved by a mechanism that is driven by an electric motor. When horizontal the surface is 1.8 m above the ground. The table was placed far from the walls of the laboratory and great care was taken to avoid air draughts in the laboratory during the experiments in order to avoid disturbances. These experiments were carried out in July and September 2002.

*Canyon Table DE 2*

The Canyon Table was described in Viegas and Pita (2002). It is similar to DV2 but its surface is formed by two rectangles (1.5 m × 3 m each) hinged along the centre line of the table. These rectangles can be inclined at any desired angle \(0^\circ < \delta < 40^\circ\) forming a canyon with arbitrary geometry. The results reported here were obtained for a slope \(\delta = 20^\circ\) and \(0^\circ < \alpha < 40^\circ\). The distance of the fire front from the origin of the fire, measured along the centre line of the table for up-slope and down-slope propagation is reported here. These experiments were carried out in June 2002.

The fuel beds used in the experiments reported here were made with dead pine needles (Pinus pinaster) with a fuel load \(M_c\) in the range between 0.6 and 1.0 kg m\(^{-2}\). Moisture content was monitored before each experiment; its value was usually in the range between 8 and 13% (dry basis).
In order to determine the rate of spread of the fire front a series of cotton strings was placed at fixed distances across the fuel bed. The distance between these strings was in the range 10–50 cm, depending on the size of the fuel bed and of the expected rate of spread.

During the experiment the time taken by the fire to burn each line was registered by at least two observers using stopwatches with an error of less than 0.1 s. This method is very simple and easy to apply in the laboratory and even in the field. It allows an objective assessment of fire advance and therefore we adopted it extensively.

The basic rate of spread $R_o$ for a linear fire front in the same fuel bed in the absence of slope and wind was determined in each series of experiments in order to characterise the basic fuel bed properties and to account for slight changes on the combustibility of the fuel from one series of tests to another. Typically two tests to determine $R_o$ were made for each series of three or four main experiments using the same type of particles and whenever possible on the same test rig. The average value of $R_o$ was then used to characterise all the tests in that session. The corresponding value of $R_o$ for each test is given in Tables 2, 3 and 4.

In the last years a complementary method using the analysis of video and infrared images of fire advance is being used. The equivalence between both methods in all cases is not yet demonstrated. The tests made in the Canyon Table were analysed using infrared images as the use of strings was not practicable on this table. Frames of the fire front taken at given time steps were analysed using an original method to correct image distortions due to non-orthogonality of the optical axis of the camera in relation to the fuel bed.

The fires were ignited either as point source fires or as linear fires. In the first case a ball of cotton soaked in alcohol was placed over the fuel bed at a pre-defined place and ignited.
with a match. Linear ignitions were produced using one or more threads of wool soaked in a mixture of petrol and fuel oil and ignited with one or two matches. A linear flame was obtained along the thread placed at or near the edge of the fuel bed in less than 5 s.

Analysis

In each test a set of points $P_i(x_i, t_i)$ was obtained for the advance of the fire front. Each point $P_i$ is defined by distance $x_i$ to the fire origin and by the time $t_i$ elapsed since ignition till the fire reached that reference distance. The number of points was at least 3 but in many cases it was above 10. The number of points for each test is indicated in the corresponding Tables 2, 3 and 4. Using an Excel program two functions were fitted to each distribution of points with the following equations.

Linear equation:

$$x_i = a_1 \cdot t + b_1,$$  (10)

with correlation $r_1^2$ and derivative

$$R_1 = a_1.$$  (11)

Quadratic equation:

$$x_q = a_2 \cdot t^2 + b_2 \cdot t + c_2,$$  (12)

with correlation $r_2^2$ and derivative

$$R_2 = 2 \cdot a_2 \cdot t + b_2.$$  (13)

As could be expected the correlation coefficient for quadratic fitting was generally greater than that for linear fitting. There were nevertheless cases in which the difference was not very important.

It is obvious that equations (10) and (11) correspond to a constant rate of spread while the quadratic fitting (equation 12) produces a variable rate of spread (equation 13). Depending on the sign of $a_2$ the rate of spread either decreased or increased from the start of the test to its end. Given the relatively low values of $a_2$ we could assume that its sign could be a result of random errors related to the experimental method.

It was found nevertheless that this was not the case in most circumstances and that there was a consistent trend in the variation of the rate of spread during the test that could be justified on physical basis.

The total duration $t_{TOT}$ of the experiment was considered to be the time elapsed since fire start until the head or the rear of the fire front reached the edge of the table. This value was registered in each case and it is given in Tables 2, 3 and 4. In order to assess the relative variation—increase or decrease—of the rate of spread during each test the following characteristic values were computed using equation (13):

- Initial rate of spread $R_{in} \quad t = 0$
- Intermediate rate of spread $R_{med} \quad t = 0.5 \cdot t_{TOT}$
- Final rate of spread $R_{fin} \quad t = t_{TOT}$

The intermediate rate of spread $R_{med}$ was usually very close to the value estimated using the linear fit: $R_{med} \approx a_1$; therefore we shall refer to it as the average rate of spread as well, although the meaning of this average value is not very evident in many cases as will be shown.

The case of a linear fire front without slope and without wind was the situation for which the linear fitting worked best and a practically constant rate of spread existed. This basic rate of spread can therefore be considered an intrinsic property of the fuel bed as it incorporates the dependence of the rate of spread on fuel bed properties, namely on its fuel load and on the moisture content of its particles. The basic rate of spread $R_o$ will be used as a reference in order to present the results in a non-dimensional form:

$$\frac{R'}{R_o} = R/R_o.$$  (14)

This formulation of using a non-dimensional rate of spread was used by several authors, namely by Rothermel (1972) and Viegas (2002). It has the advantage of generalising the experimental results to other fuel bed conditions, at least in a limited range of variation of the fuel bed properties.

As the basic rate of spread $R_o$ was defined for a linear fire front for a horizontal fuel bed in the absence of wind, it must be realised that the corresponding value of $R/R_o$ for point source fires in the same conditions is in general smaller than 1. Discrepancies that can be observed in Tables 2 and 3

<table>
<thead>
<tr>
<th>Point ignition</th>
<th>a (°)</th>
<th>$a_1$ (cm s$^{-1}$)</th>
<th>$r_1^2$</th>
<th>$a_2$ (cm s$^{-2}$)</th>
<th>$b_2$ (cm s$^{-1}$)</th>
<th>$r_2^2$</th>
<th>$t_{TOT}$ (s)</th>
<th>n</th>
<th>$R_o$ (cm s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE2–514</td>
<td>–40</td>
<td>0.224</td>
<td>0.983</td>
<td>0.0007</td>
<td>0.0934</td>
<td>0.997</td>
<td>160</td>
<td>8</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–513</td>
<td>–30</td>
<td>0.314</td>
<td>0.993</td>
<td>–0.0002</td>
<td>0.3530</td>
<td>0.993</td>
<td>140</td>
<td>8</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–512</td>
<td>–20</td>
<td>0.175</td>
<td>0.964</td>
<td>0.0007</td>
<td>0.0600</td>
<td>0.979</td>
<td>180</td>
<td>9</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–511</td>
<td>–10</td>
<td>0.269</td>
<td>0.993</td>
<td>0.0003</td>
<td>0.2110</td>
<td>0.996</td>
<td>200</td>
<td>11</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–510</td>
<td>0</td>
<td>0.258</td>
<td>0.993</td>
<td>0.0004</td>
<td>0.1740</td>
<td>0.997</td>
<td>630</td>
<td>22</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–511</td>
<td>10</td>
<td>0.486</td>
<td>0.995</td>
<td>0.0004</td>
<td>0.3711</td>
<td>0.998</td>
<td>300</td>
<td>16</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–512</td>
<td>20</td>
<td>0.803</td>
<td>0.926</td>
<td>0.0032</td>
<td>0.0949</td>
<td>0.995</td>
<td>230</td>
<td>13</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–513</td>
<td>30</td>
<td>1.190</td>
<td>0.850</td>
<td>0.0118</td>
<td>–0.9230</td>
<td>0.982</td>
<td>160</td>
<td>9</td>
<td>0.340</td>
</tr>
<tr>
<td>DE2–514</td>
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<td>1.160</td>
<td>0.753</td>
<td>0.0161</td>
<td>–1.7100</td>
<td>0.945</td>
<td>160</td>
<td>17</td>
<td>0.340</td>
</tr>
</tbody>
</table>
for the no-slope and no-wind cases may de derived from the difference in boundary conditions for fire spread in both rigs: presence of vertical walls in the Combustion Tunnel in contrast to no walls in the Inclination Table.

In order to characterise the relative magnitude of the rate of spread variation during each test, parameter $a_2$ will be used. This coefficient was defined in equation (12) and it is a measure of the rate of spread change per unit time. The sign of $a_2$ indicates if the rate of spread increased during fire growth ($a_2 > 0$) or if it decreased ($a_2 < 0$). Values of $a_2$ are given in Tables 2, 3 and 4 and plotted in Fig. 16.

**Results and discussion**

**Wind**

The properties of the experiments performed in the Combustion Tunnel for point and linear fires are given in Table 2. For each experiment the values of the relevant coefficients $a_1$, $a_2$ and $b_2$ are given, together with the correlation coefficients $r^2_1$ and $r^2_3$, the flow velocity $U_o$, the total time $t_{TOT}$ and the number of points $n$.

The results obtained for the tests performed with wind driven fires for point and line ignition are shown in Figs 9 and 10, respectively. In each case three lines are plotted showing the non-dimensional $R/R_o$ rate of spread variation with wind velocity. These lines represent the initial, the intermediate and the final rate of spread computed for each case using equation (12) as described above. In each test it is easy to see if the rate of spread increased ($R_{fin} > R_{med}$) or decreased ($R_{fin} < R_{med}$) from the start to the end of the experiment. In order to make this interpretation more clear for backing fire spread (negative values of wind velocity), the corresponding part of the graph is enlarged in each case as part (b) of Figs 8, 9 and 10, respectively. A similar presentation of the results is used for the other two cases.

The average rate of spread increases with wind velocity both for forward and backward spread (positive and negative values of $U_o$). For point ignition fires the value of $R$ reaches 23 for a wind velocity of 4.4 m s$^{-1}$. The corresponding value for line source fires is around 40.

As can be seen from the values of $a_2$ that are shown in Table 2 for point ignition fires with constant wind velocity, the rate of spread increases during fire growth for forward spread and decreases for backward spread. There is nevertheless one case of forward spread that does not follow this rule. The magnitude of the variation of the rate of spread is small in all cases. In spite of the variation of the rate of spread it is reasonable to define a rate of spread of the head fire in each case.

Weise and Biging (1996, 1997) report the results of average rate of spread of line source fires performed in a laboratory facility in which wind and slope could be modified simultaneously. Their results on the separate effects of wind or slope on the average rate of spread are comparable to the present ones. In these experiments, rate of spread was measured using nine pairs of thermocouples spaced equidistantly along the fuel bed. Apparently a linear fit was used for distance v. time data as these authors do not report any fire acceleration.

McAlpine and Wakimoto (1991) obtained a similar change in the rate of spread in a series of laboratory experiments of point source fires driven by wind. Although their curves of distance v. time resemble second-order polynomials in their analysis of fire acceleration to equilibrium spread they elected to fit empirical exponential or power laws to describe the rate of spread variation with time.

As predicted in the previous analysis for line ignition fires (Fig. 9), the contrary seems to happen. The reduction of $R$ during fire spread was also observed in the laboratory tests reported by Wolff et al. (1991). The rate of spread decreases during the test; at least for high values of the wind velocity the magnitude of the variation is quite large. The definition
of a rate of spread value in each test becomes problematic and discrepancies between authors using different test rigs to evaluate the rate of spread from wind driven fires can be easily explained. There is again one case that does not follow this rule.

For backward spread it is observed that the behaviour changes with increasing wind velocity: for low values of \( |U_o| \) the rate of spread decreases during the test while for higher values of \( |U_o| \) the contrary happens.

The corresponding values of \( r^2 \) are shown in Fig. 10. As can be seen the values of \( r^2_q \) are practically always greater than the corresponding values of \( r^2_l \). For point ignition fires and for forward spread there is practically no difference between the linear and the quadratic fitting, thus confirming that the rate of spread is practically constant in these cases. Somewhat surprisingly, that is not the case for backward spread.

For line source fires, linear fitting is not bad for negative values of \( U_o \) but for forward spread it is always worse than the quadratic fitting.

Slope

The properties of the experiments performed in the Inclination Table DV2 for point and linear fires are given in Table 3. The results obtained for the rate of spread with varying slope for point and line source fires are shown in Figs 12 and 13, respectively.

The relative increase of the average rate of spread with \( \alpha \) is not so large as was observed for wind-driven fires. The maximum values of \( R'_{\text{med}} \) measured for \( \alpha = 40^\circ \), for point and line source fires were respectively around 4 and 20.

For point ignition fires it is found that the rate of spread increases during each test with fire growth. This is observed consistently for forward and backward spread (positive and negative values of \( \alpha \)) as well (cf. Fig. 11). The relative variation of the rate of spread for values of \( \alpha > 30^\circ \) is quite important; this was not observed for wind driven fires.

For line source fires the rate of spread decreases along the fire development for forward spread (positive values of \( \alpha \),
just as happened for wind driven line fires. As can be seen in Fig. 12b for backward spread, the behaviour is not very clear. Apparently the rate of spread decreases for moderate values of $\alpha$ and then it increases for $\alpha < -30^\circ$. Van Wagner (1988) reports this same behaviour in a series of laboratory experiments. A similar pattern was observed for wind-driven back fires as well in the present experiments (Fig. 8).

The average value $R'_{\text{med}}$ of the rate of spread remains practically constant for backward spread. This is a difference between wind- and slope-driven fires.

The correlation coefficients $r^2$ are shown in Fig. 13 for both cases. As can be seen there is not much difference between linear or quadratic fittings for $-30^\circ < \alpha < 20^\circ$ for both point and line source fires.

Canyon

The properties of the experiments performed in the Canyon Table for point fires are given in Table 4. The results obtained for the rate of spread of the fire along the canyon symmetry line with varying slope for point source fires are shown in Fig. 14.

It is observed that the rate of spread increases with fire growth both for the up-slope and for the down-slope sections of the fire. The relative increase of the rate of spread for values of $\alpha > 20^\circ$ is very important. It is observed that the fire starts to spread with a very low velocity and then it starts to increase continuously in the so-called ‘blow-up’ phenomenon. As can be seen in Fig. 15 even the correlation coefficient of the quadratic fitting for $\alpha > 30^\circ$ is not satisfactory. This means that probably a higher coefficient power law or even an exponential law would be more appropriate to describe head fire temporal evolution in these cases.

The average rate of spread $R'_{\text{med}}$ decreases with negative slope as can be observed in Fig. 14b.

Fire acceleration

The distribution of $a_2$ defined by equation (11) indicates the relative magnitude and sign of the rate of spread variation
with fire growth in each case. The results obtained are presented in Fig. 16. In order to make this figure more clear the values of $a_2$ were multiplied by $10^5$ and are given in SI units (m s$^{-2}$). Figure 16 summarises the differences between the four factors that were considered: (i) ignition mode; (ii) wind velocity; (iii) slope angle; and (iv) canyon inclination. As can be seen in that figure, low values of $|a_2|$ are associated with low values of wind velocity or terrain inclination. We can consider that when $|a_2| > 5 \times 10^{-5}$ m s$^{-2}$ the definition of an average rate of spread becomes problematic for the present laboratory conditions.

High values of $|a_2|$ associated with back fires are not very important in practical terms. They correspond to back fires with a relatively low rate of spread. As remarked by Cheney and Gould (1997) any error in the estimation of such a rate of spread is usually acceptable by fire managers. The same cannot be said for the forward rate of spread prediction errors.

The results obtained for the variation of the rate of spread during each test for the various cases that were studied are summarised in Table 5.

**Conclusion**

In this paper the problem of the existence of a steady-state regime for fire propagation evaluated by a constancy of its rate of spread value for a fire front in a uniform fuel-bed under uniform spatial and permanent time dependent boundary conditions was addressed.

A qualitative analysis and interpretation of fire growth of some very simple cases showed that it was not very likely to have a constant rate of spread during fire development. Depending on the type of ignition (point or line source fires) for forward slope or wind, we can expect a positive or a negative acceleration of the fire front, respectively.

Laboratory experiments carried out with carefully controlled conditions demonstrated that the qualitative analysis is essentially correct. These experiments showed that, although wind and slope mechanisms are similar, they
produce different effects on fire behaviour as noted above. It was observed in general that whenever slope or wind has an important magnitude the rate of spread does not remain constant.

It was also shown that in canyon fires the rate of spread can increase dramatically even at the small scale of a laboratory table under calm conditions. This result is very important for the analysis of fatal accidents that occur in canyons, as it shows that the so-called ‘blow-up’ that is observed in these conditions is an intrinsic property of the concave shape of the terrain. They can occur even in the absence of wind at all, let alone some particular weather conditions that are some times invoked to explain those accidents.

In theoretical terms we can conclude that, as there are cases for which there is not a constant and well-defined rate of spread value, the existence of a steady-state cannot be assumed as a general condition for fire spread. It must be remarked that the cases that were dealt with in this paper were some of the simplest situations that can be found in fire spread. They are precisely some of the cases for which one would expect that a steady-state regime would be attained. It was demonstrated that in the general case one cannot expect to derive a unique value of the rate of spread of the fire front. Apparently the rate of spread value is time dependent and one needs to know the time story of the fire in order to evaluate its rate of spread to predict its evolution. This fact explains partially the large scatter that is found by different researchers in measured values of rate of spread even for the nominally same conditions. This study showed that, depending on the period of fire growth in which rate of spread is measured in a given experiment, one may find a range of values even for the same boundary conditions.

This conclusion brings an added complexity to the problem of fire behaviour modelling and analysis making the acceptance of some simplifying assumptions such as the

Table 5. Summary of relative variation of the rate of spread during each test

<table>
<thead>
<tr>
<th>Config.</th>
<th>Effect</th>
<th>Point ignition</th>
<th>Line ignition</th>
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</thead>
<tbody>
<tr>
<td>Slope</td>
<td>Positive</td>
<td>$R$ grows</td>
<td>$R$ decreases</td>
</tr>
<tr>
<td>Wind</td>
<td>Negative</td>
<td>$R$ grows</td>
<td>$R$ decreases and then grows</td>
</tr>
<tr>
<td>Canyon</td>
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This conclusion brings an added complexity to the problem of fire behaviour modelling and analysis making the acceptance of some simplifying assumptions such as the
existence of a quasi-steady regime a bit more difficult. It is hoped that further research on this point will bring more light to these questions.

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References


McAlpine RS, Wakimoto RH (1991) The acceleration of fire from point source to equilibrium spread. Forest Science 37, 1314–1337.


Viegas DX, Neto LP (1991) Wall shear-stress as a parameter to correlate the rate of spread of a wind induced forest fire. International Journal of Wildland Fire 1, 177–188.


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