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Phil. Trans. R. Soc. Lond. A 1998 **356**, 2907-2928
doi: 10.1098/rsta.1998.0303

THE ROYAL SOCIETY

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The different phases in the development of forest fires and propagation regimes are characterized, together with the main factors affecting them. The problems of modelling the various fire behaviour regimes are mentioned, with particular relevance to surface fire propagation, both locally and globally. The role of convection and radiation processes on fire propagation is considered. From a set of laboratory experiments on the propagation of a linear fire front on an inclined surface, the linkage between convection and radiation in the fire propagation process is demonstrated. This result is generalized for wind-driven fires and an interpretation for the global movement of the fire front under slope or wind conditions is presented.

Keywords: forest fires; fire dynamics; fire behaviour modelling; wind/slope effects; fire line rotation; surface firespread

1. Introduction

Fire is a natural element that is a part of the forest ecosystem. Human intervention in nature has been based usually on the exclusion of fire from the forest. This and other factors have created conditions under which an increasing number of wildfires, that burn large areas of the forest, occur throughout the world. Following ancestral practices, in some regions fire has been reintroduced in the forest in the form of controlled fires, which are sometimes caused by man and sometimes are natural fires that are left burning in controlled conditions. One of the purposes of these controlled fires is to manage vegetation growth, in order to avoid its accumulation, which could lead to disastrous wildfires. In spite of the different ambient conditions under which controlled fires and wildfires occur, the same basic principles of propagation apply to both. Therefore no distinction shall be made in this paper between controlled and wildfires, and the more common term of forest fires shall be used throughout the text.

Undesired forest fires are one of the major natural disasters that threaten the environment in various regions of the world. Each year many thousands of hectares of vegetation-covered areas are consumed by fires caused by man or nature, endangering not only the natural environment, but also socio-economic life and quite often human life itself.

Forest fires constitute a very complex problem given the large number of factors that affect them. In most countries their prevention and mitigation require a multi-institutional approach in order to cope with their various aspects and specific problems. From a scientific point of view, several disciplines are also required to cooperate in the analysis of the problem. The works by Chandler *et al.* (1983), Brown & Davis (1973), Pyne (1984) and Pyne *et al.* (1996) give an excellent overview of different aspects related to forest fires. In spite of the very different climatic and

Phil. Trans. R. Soc. Lond. A (1998) **356**, 2907–2928

Printed in Great Britain

TEX Paper

socio-economical conditions in which forest fires may occur, there are some common physical factors that play a major role in determining their potential incidence and propagation. These factors will be the main subject of this paper.

In the context of this paper we consider a forest fire to be one in which natural vegetation is consumed, without regard to the fact that it may be composed of developed trees, constituting a real forest, or just be shrub land or an even agricultural area. For this reason some authors prefer to use the designation of rural fires, to include all those kinds of fires in which dead or living plants support the propagation of the fire front. A common feature of these fires is that the fuel is a solid porous material composed of organic products and essentially cellulose.

Scientific research into the behaviour of forest fires has mainly been developed over the past 50 years. Some countries, such as the USA, Canada, Russia and Australia, established their first comprehensive research programmes quite early, corresponding to the public perception of this problem. In Europe it is worth mentioning the pioneering work by Thomas (1962, 1967, 1971); in the past 15 years, particularly with the support of the European Union, a large number of research projects have been developed. A survey of research in the field is not appropriate here but a general overview of past research on physical aspects of forest fires is given in André *et al.* (1992).

In this paper an overall view of the physical phenomena occurring in forest fires is given, with particular emphasis on fire dynamics. A general description of the different phases of development and fire propagation regimes is presented and a characterization of the relevant factors affecting these processes is made. Typical time- and space-scales used in the modelling of fire propagation are defined and the main problems associated with the prediction of fire behaviour are addressed. The unstable characteristic of wind- or slope-driven fire fronts is shown and an interpretation of the evolution of the fire front is proposed. The contents of this paper reflect the experience of the author and of his team over 12 years of research on the subject of forest fire propagation.

2. Fire propagation phases and regimes

(*a*) *Phases of development of a forest fire*

At a given spatial location in a forest fire the following temporal phases of development can be observed in succession:

(i) preheating and pyrolysis;

(ii) ignition;

(iii) initial growth;

(iv) secondary growth;

(v) flame decay;

(vi) extinction; and

(vii) cooling.

A detailed description of these phases can be found, for example, in Steward (1974) or Pyne (1984). Details on the physical and chemical phenomena occurring in phases (i) and (ii) are given in Williams (1982), Chigier (1981) and Drysdale (1992). Some phases, like (iii) or (iv), may not occur in certain fires, depending on the boundary conditions, as will be discussed below. To start a fire an external source of heat is required, as self-ignition is virtually impossible in these types of fuels, but once the exothermic combustion reaction is established it is self-sustained, except in some particular conditions of marginal propagation or extinction. Given the limited availability of fuel at a particular location, for a fire to sustain itself it must necessarily propagate to neighbouring vegetation. This process of fire spread is a characteristic of forest fires and depends on so many factors that two given events may have a time duration and a spatial extension varying by several orders of magnitude from each other.

At the ignition phase we assume that the fuel is in self-sustained combustion without flames. The initial growth phase corresponds to the passage of slow combustion to flaming combustion. In some fuels these two phases are indistinguishable. The secondary growth corresponds to the evolution of the flaming reaction from the material near the ground surface to the upper layers of the vegetation, i.e. to the foliage of the tree canopies. This type of fire propagation regime is also called crown fire propagation. This secondary growth is not just an amplification of the previous situation and it deserves to be treated as a separate phase because there are some qualitative differences between both phases, besides the quantitative differences.

At different stages the fire may decay to a lower regime until total fire extinction is reached. In the general case, a crown fire will decay and propagate as a surface fire, with a flaming fire front. If the flames are extinguished the fire may propagate as a ground fire and finally, when glowing combustion is extinguished, bring the fire process to its final state.

The above-described process of growth and decay is not a closed one, in the sense that at a given place a decaying ground fire may grow and spread again as a flaming fire or even experience a secondary growth and propagate as a crown fire at a later stage.

(*b*) *Regimes of propagation*

We can identify three main stable regimes of fire propagation, according to the main fuel layers that are involved in the combustion process: (i) ground fire; (ii) surface fire; and (iii) crown fire.

Ground fires burn usually without flame in the organic layer above the mineral soil, their propagation is very slow and although they do not pose a great threat to the upper layers of the vegetation cover, they can produce considerable damage to the soil given their large residence time. In some particular conditions these ground fires can have an initial growth and become flaming surface fires. This is quite common in the decaying phase of fires that are not completely extinguished; i.e. they may rekindle and start another loop in the fire development process.

Surface fire is the most common propagation regime, in which a wide class of vegetation litter, dead and live fine fuels at or near the soil surface, can be consumed in a flaming combustion. For various reasons this fire propagation regime is the best studied, and unless stated otherwise we shall deal with surface fire propagation in this paper.

If conditions are favourable, a surface fire propagating under tree canopies may extend to the upper layers of the crown foliage. A single tree or a group of trees will be torched by such a fire. If there is horizontal continuity in the canopies and if the foliage moisture content is below a given threshold, a sustained crown fire propagation regime will be achieved. Given the fact that the tops of the tree canopies are exposed to higher wind velocities these crown fires may propagate with very high rates of spread. The height of the flames associated with such crown fires may be so large that the interaction between the fire and its surrounding will involve a substantial part of the atmospheric boundary layer. This interaction creates a feedback mechanism that modifies the atmospheric flow in the vicinity of the fire in a manner that is much more intense compared to that of a surface fire. This is especially the case when large masses of vegetation are burning simultaneously under weak wind, in which the convection column above the fire is associated with a strong horizontal flow near the ground that entrains air into the combustion zone. Under very strong winds these intense fires may experience high rates of spread, have the capacity to destroy large areas of forest land, and are very difficult to suppress. The vertical extension of the influence zone of the combustion reaction and its associated convective processes render the effects of topography or vegetation cover, that are discussed below, to be of relatively less importance. The threshold conditions required for a surface fire to spread to the crowns have been studied by Van Wagner (1977*a*), but are still a subject of research today. It is found that usually crown fires do not burn uniformly large areas of the forest, tending to form more or less heterogeneous patterns, due to the complex interaction of the convective flow and the tree canopies.

Burning embers can be carried aloft by the strong convection produced at the fire front, particularly in crown fires, transported by wind and scattered ahead of the main fire front, causing spot fires. These secondary spot fires are a common feature of this regime of fire propagation, but they may also occur in surface fires, contributing to an increase in their degree of danger.

(*c*) *Factors affecting fire propagation*

The physical factors that have a significant influence on the initiation and on the development of a forest fire are usually grouped into three categories.

(i) *Topography*

The terrain configuration at the location of the fire, namely its altitude, slope, solar exposition and the overall surroundings determine the type of climate, vegetation cover and the wind pattern near the ground. For practical purposes, in the scope of this paper we shall retain the local slope as the main topography element affecting directly the fire propagation. The slope angle α of vegetation-covered areas can vary from 0–40°; for a given fuel the rate of spread of downslope-propagating fires is quite low and practically constant, while the rate of spread of a fire front propagating upslope increases with α.

(ii) *Vegetation*

As stated above, forest fuels consume parts of vegetation, that can exhibit different forms and spatial arrangements, constituting a solid porous fuel bed with one or more layers. The parts of the plants that participate in the propagation of the majority of forest fires are the so called fine particles, for which there is a typical minimum dimension (thickness or diameter) of less than, say, 6 mm. Only in very intense fires will larger particles burn during the spread of the fire front, although they may be consumed after its passage. It is usual to consider three layers of fuel particles: (a) the ground layer, with organic residues and decomposing litter, just above the mineral soil; (b) the surface layer, consisting of the fuel on, or in, the close vicinity of the ground surface, i.e. litter, herbaceous shrubs and small trees; and (c) the canopy layer, formed by the foliage of the trees. Each of these layers can be characterized globally (Rothermel 1972) by its height or thickness, porosity, fuel load, and vertical and horizontal continuity. Each layer is usually a mixture of particles of different species, sizes and shapes, that may be alive or dead. The chemical composition of the particles may vary from one species to another, and with the period of the year, but this is not a particularly relevant factor in terms of heat release from the unit of mass (Philpot & Mutch 1971). The water or moisture content of the fuel particles, as well as its mineral content, act as a heat sink or even as a chemical inhibitor in the pyrolysis process and therefore have a major influence on the fire ignition and fire spread properties. Its effect on the daily number of fires and burned area in the central region of Portugal was shown in Viegas *et al*. (1992). The moisture content of fuel particles depends greatly on the long- and short-term meteorological conditions; dead, fine fuel particles may appreciably change their moisture content in a period of a few hours, while heavier or living particles require longer time-periods. For a given fuel bed, the basic rate of spread R_0 of a fire front propagating in a horizontal fuel bed in the absence of wind, decreases with the moisture content and above a certain threshold—moisture of extinction—fire ignition and propagation are virtually impossible. Results obtained by the author in a series of laboratory experiments in a combustion table ($1.2 \times 2.2\ \mathrm{m}^2$) with dead *Pinus pinaster* needles, with a fuel load of $1\ \mathrm{kg\ m}^{-2}$, are shown in figure 1 to illustrate this effect. Similar results are reported by other authors for the same effect, for different forest fuels (see, for example, Rothermel 1972).

(iii) *Meteorology*

Meteorological conditions are the most changeable factor in the fire propagation process. The following parameters are usually considered to be the most relevant: air temperature, air humidity, precipitation, solar radiation, atmospheric stability, vertical profile of wind velocity and direction. The first four parameters have a determining influence on the moisture content of the fuel particles and are therefore related to the so-called meteorological fire danger level. Some of these factors have a cumulative effect on the fire danger level. In Viegas *et al*. (1994), a description and a comparative study of some known methods for fire danger prediction are given. Precipitation may have a long- or a short-term effect, as shown in Viegas & Viegas (1994). Wind and vertical stability patterns are mostly associated with fire spread conditions. Wind is recognized to be by far the single most important factor in the entire problem of forest fire propagation. Given the spatial and temporal variability of wind, in practice it is not possible to have a fire propagating in uniform and stable conditions for any measurable period of time. The ability to estimate wind distribution near the vegetation surface and its time-evolution is therefore of utmost

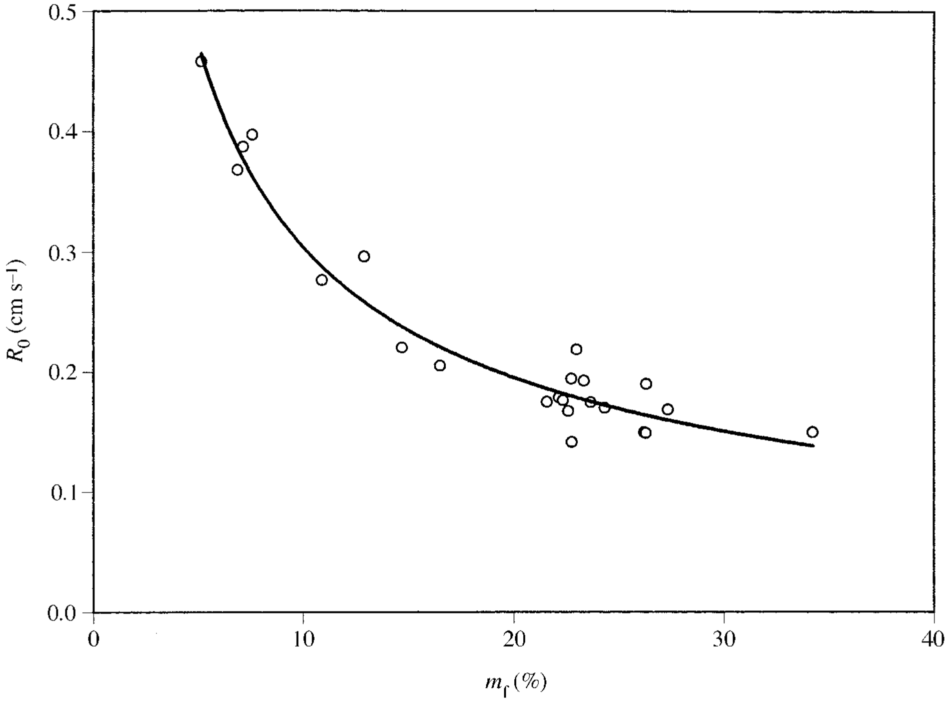

Figure 1. Rate of spread R_0 of a linear fire front in a *Pinus pinaster* needles fuel bed as a function of fuel moisture content m_f. The fuel load is 1 kg m^{-2} and the width of the fuel bed is 1.2 m.

importance for dealing with the problem of fire propagation. The strong gradient of the wind velocity profile near the ground raises the problem of defining and estimating a reference wind velocity to characterize the interaction between the wind flow and the fire front (Albini 1981; Baughman & Albini 1981). Based on physical considerations, the author proposed (Viegas & Neto 1991) the use of the wall shear stress, or its equivalent friction velocity $\boldsymbol{u}_\tau$, produced by the flow on the fuel layer, for that purpose. As is well known, in turbulent boundary layers over a rough surface, in the absence of pressure gradients, the value of $\boldsymbol{u}_\tau$, together with the roughness height and displacement parameters z_0 and d_0, defines the velocity profile near the surface. Nevertheless, in this paper we shall use wind velocity $\boldsymbol{U}$ to refer to wind effect, as it is a more intuitive and familiar parameter.

(*d*) *Fire propagation modelling*

The ability to describe the propagation of a fire with a set of quantitative rules has been the aim of many research programmes throughout the world in recent years. Given the number of factors involved, it is understandable that even for nominally stable propagation regimes, there are no general models yet available to perform this task with a sufficient degree of accuracy and reliability. The problem of fire propagation modelling involves the specification of the boundary conditions, which include at least a complete description of the three relevant groups of parameters mentioned above, before and during fire propagation. A model of the transient phases of fire from start through its development would require the solution of time-dependent equations of very complex physical phenomena. To the author's knowledge, there are very few examples of such studies in this field. Weber (1989) proposed an analytical solution of the growth of a circular fire front, originated at a single point, taking into account the curvature effect of the fire front. An attempt to describe the response of the fire to wind variations was made by Albini (1982a, b); this work gives some insight into the relevant parameters involved but it is yet to be validated. The solution of the permanent regime, with nominally constant boundary conditions, is of course easier to achieve, as it requires fewer parameters to be described and known.

There is a wide range of fire propagation models, ranging from the purely empirical to the purely physical. For a critical survey of existing models, see Rothermel (1990) and André *et al*. (1992). Application of empirical models is of course limited by the set of conditions for which the basic data were collected. Interesting examples of empirical models are the ones developed in Canada by the Forestry Canada Fire Danger Group (1992), in Australia by MacArthur (1966) or more recently by Sneeuwjagt & Peet (1989). Physical models, although of more general application in principle, have proved so far to be non-practical, due to the complexity of the phenomena involved and to the number and type of input data that they require, which are not easily available in most cases. Therefore, a semi-empirical approach to the problem seems to be the best choice. In these types of models assumptions are made about some of the chemical and physical processes, namely the pyrolysis and ignition of the fuel particles. Usually, the heat-transfer process from the combustion zone (heat source) to the potential fuel and to the environment (heat sink) is modelled. Some of the intermediate input parameters required in the models, like, for example, flame height or flame inclination, are obtained from empirical data. A very good example of such a model is the one developed by Albini (1985), in which radiation inside the fuel bed and from the flame front is considered as the main propagation mechanism; in Albini (1986) the cooling effect of natural convection in the potential fuel is also considered. Albini & Stocks (1986) extended the application of this model to crown-fire-spread with very reasonable results.

A semi-empirical model developed by Rothermel and co-workers (Rothermel 1972, 1983) has found widespread application throughout the world, mainly due to the fact that it requires easily observable and measurable input data to be used. This model is based on extensive experimental data, mostly obtained from carefully conducted laboratory experiments, aimed to circumvent the analytical difficulties involved in the solution of the balance between the energy released by the combustion reaction and the heat flux required for the propagation. Using several intermediate empirical functions, to cope with the various factors involved, an explicit relationship was obtained between the properties of homogeneous fuel beds and the rate of spread, including slope and wind effects. Within the range of the experiments performed, these equations therefore have a general applicability. This model is the core of the fire behaviour prediction system BEHAVE (Burgan & Rothermel 1984; Andrews 1986; Andrews & Chase 1989). The BEHAVE system is the most common basis for existing decision support systems that include some modulus of fire behaviour prediction, but quite often the model is applied to situations that fall outside its range of validity.

In view of the large discrepancies found between the predictions obtained extrapolating the BEHAVE system to large fires, Rothermel (1991) proposed an empirical model for the evaluation of the spread properties of crown fires that was developed for a particular region in the USA. The general validity of this method has not been tested yet.

(*e*) *Heat-transfer mechanisms*

The main heat-transfer processes at the fire front related to fire propagation are: convection, radiation and mass transportation. In surface fires convection is usually associated with the surface atmospheric winds or to the buoyancy-induced flows due to the low-density combustion products released in the reaction zone of the fire. In large fires these convective flows interact with the upper layers of the atmosphere creating a feedback process that requires the involvement of a larger height (of the order of 10^2 m) volume control to close the problem (Viegas 1998). Thermal radiation is of paramount importance, especially in flaming fires, given the very high temperatures that are reached in the reaction zones of the fire. There are two combustion zones at the fire front: one inside the solid porous fuel bed and the other in the gaseous phase, in the flame above the fuel bed. The radiation from the solid phase, inside the fuel bed, has a relatively short range, given the attenuation produced by the fuel particles; therefore its heat flux causes a relatively slow rate of spread of the fire front. Radiation from the flame surface depends greatly on the size and shape of the flame, namely on its inclination angle in relation to the potential fuel. If the flame is inclined towards the already burned fuel, as in contrary wind propagation, the contribution of the flame to the advance of the fire will be relatively low, the main flux coming from the reaction zone inside the fuel bed. Therefore for contrary wind, as for negative slope, the rate of spread will be very low and practically constant, as the shape of the reaction zone is not very much affected by contrary wind in this case. If the fire front is propagating with a favourable wind or upslope, the flame will be inclined towards the unburned fuel and its shape factor in relation to the fuel bed particles will be much larger. Adding to this, the favourable wind, or slope-induced convection, will usually enhance the combustion process and the flame length will increase, contributing to a more intense heat flux to the potential fuel, and consequently to a much higher rate of spread.

Mass transport as a heat-transfer process is associated with the projection, transportation and release of burning particles at the fire front that are entrained by the convection column and dropped at considerable distances from the main fire. In the event that these burning embers fall on ignitable material, a secondary fire-spot can be created, with the associated danger to the fire control process. These fire-spots are particularly common and dangerous in large fires, but in spite of their practical relevance, very few systematic studies exist about these phenomena.

(*f*) *Space- and time-scales of modelling*

Given the fact that in real life the boundary conditions are neither uniform in space nor constant in time, in a simplified modelling approach a quasi-stationary assumption must be made in order to cope with the changes of the boundary conditions that are encountered in practice. This simplification requires the introduction of the concepts of modelling temporal and spatial scales. Given the difficulty of describing in detail the vegetation cover in all its complexity and heterogeneity, it is acceptable to consider an equivalent fuel bed, or fuel model, with uniform and homogeneous properties that lead to the same fire behaviour as the actual vegetation. The problem of fuel modelling is intimately associated with that of fire behaviour modelling, as the reduced number of parameters used to characterize each fuel bed should be sufficient to distinguish it from any other model with different fire propagation properties. The BEHAVE system (Rothermel 1972, 1983; Burgan & Rothermel 1984) presents a set of 13 standard fuel models that already cover a wide range of situations; in addition it proposes a method for developing custom-made fuel models. The application of a fire propagation model requires that the size of a fuel cell, with uniform fuel properties, be sufficiently large so that the assumptions made in the model are valid; for example in the heat-transfer processes. For a flaming front this requires that the width of the cell be at least three to five times the height of the flame, in order to have only minor edge effects. Temporal scales are limited by the variations in fire spread due both to spatial changes in the vegetation or topography along the fire path, or to temporal modification of meteorological parameters, namely wind. Sudden changes in any of these properties will induce a dynamic response of the fire that will adapt itself to the new conditions with a certain time lag. In the opinion of this author, time-scales associated with wind changes are dominant and, therefore, temporal scales should be defined by the periods in which wind properties can be considered to be relatively constant, which are typically of the order of ten minutes. For practical applications a constraint may also be placed by the availability of wind data at such a detailed period of time.

(*g*) *Local and global ranges*

In the management of forest fire suppression tactics one is usually interested in predicting the overall time-evolution of the entire fire front. This is the so-called global range modelling problem (André 1996) that consists of determining the location of the fire front at any given time-step specifying all the required boundary conditions. With the exception of the trivial situation in which all the properties are uniform in space and constant in time, to solve this problem it is necessary to break the time lapse into smaller intervals so that quasi-uniform conditions can be assumed during each time-step.

One other approach to the problem of fire propagation modelling is to consider a section of the fire front and analyse its properties given the local ambient conditions; this is the so-called local range problem. It is easy to see that both problems are not independent, and that the local range problem is only a conceptual partition of the global problem. The concept of local range is quite useful for analytical and experimental purposes, but its application has some restrictions that shall be made clear in the following.

In most cases a forest fire is started at a single point, and develops first as a circle, that gradually changes its size and shape according to the boundary conditions. Due to non-uniform or non-permanent boundary conditions, the fire front will develop distinct parts along its perimeter. The main fire front, that propagates pushed by wind or slope, is appropriately called the head of the fire. This part of the fire front is usually its most intense section in terms of high values of the rate of spread and of the heat release per unit of time and per unit of fire line length. The sides or flanks of the fire front have a relatively lower rate of spread. The back of the fire closes its contour and it is composed of a section of the fire in which fire is spreading contrary to wind or to slope effect. According to some authors (Anderson 1968; but

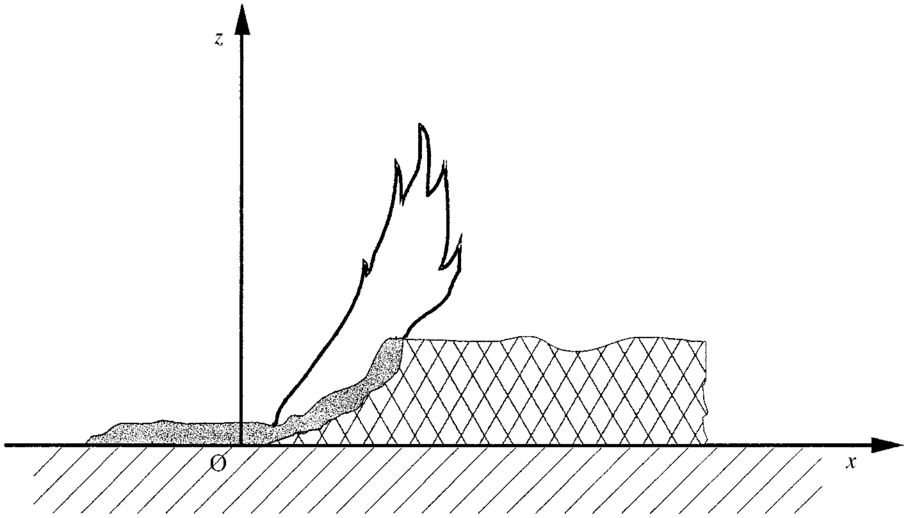

Figure 2. Schematic view of a section of a linear fire front for the local range problem. The properties are assumed to be uniform along the Oy-axis (perpendicular to the figure).

see also Green *et al*. 1983; Bilgili & Methven 1990), the contour of the fire front can be represented by a simple or a double ellipse, with a shape that depends on the slope gradient and on the wind velocity and direction. Catchpole *et al*. (1982) introduced a kind of Huygen's principle to describe the evolution of a fire front at arbitrary spatial and time conditions. According to this approach, each segment of the fire line is to be treated as an independent element that propagates as a virtual elliptic fire front, the properties of which depend only on the local conditions at that point. André (1996) analysed the equivalence of various algorithms to explore this and similar concepts to deal with the prediction of the fire front shape. Richards (1995) and Richards & Bryce (1995) applied this concept and tested it on several case studies in order to evaluate its robustness.

In very large fires, or fires burning in complex topography or heterogeneous fuel, the fire front may develop multiple heads, flanks and fingers. These constitute separate sections of the same closed fire front, that may or may not interact with each other, depending upon their local conditions and on their range of influence in relation to the global fire.

Turning back to the local range problem, in its most basic form, one considers a straight segment of the fire front propagating in a uniform fuel on a horizontal surface in the absence of wind. If the reference axis system is suitably arranged, as illustrated in figure 2, then the direction of the rate-of-spread vector $\boldsymbol{R}$ is clearly defined to be perpendicular to the fire front and therefore parallel to the Ox-axis. In this model the Oy-coordinate is not considered, because all the properties are assumed to be uniform along Oy, i.e. $\partial/\partial y \equiv 0$, and consequently there are no fluxes across vertical planes parallel to the Ox-axis. Many numerical and laboratory studies have considered this ideal and simplified situation in order to analyse the mechanisms that occur at the fire front and to understand their role in fire propagation. The solution of even this simplified problem would certainly bring much light to the entire fire propagation modelling. Unfortunately, such a solution does not yet exist, to the knowledge of the author, and besides this the described situation occurs only in very restricted parts of the fire line. In most cases perpendicular properties of the fire front are not uniform and therefore the basic assumption of independence in relation to Oy, and the absence of fluxes along the fire line perimeter, is not valid. This is particularly true when the rate-of-spread vector $\boldsymbol{R}$ is not aligned with the wind velocity $\boldsymbol{U}$, or slope-gradient vector $\boldsymbol{S}$, as will be shown below for a particular case.

In finite fire fronts found in practice, both in the field and in the laboratory, unless the height (H) of the flame front is much less than its width (B) (measured along Oy), the restriction to a two-dimensional problem will not hold. It is easy to see that if $H/B \approx 1$ the radiative heat flux to the potential fuel along a line parallel to the finite fire front decreases from the symmetry plane to its edges. Under these conditions the rate of spread of the fire will not be uniform along its entire length. If for some reason the flame height or the flame angle is not uniform along Oy, this effect will be enhanced, separating this situation from the ideal two-dimensional case described above.

In conclusion, in the opinion of the author, the restrictive concept of a local range model is an interesting tool for analysing and understanding the physical processes at the fire front, and to establish the role of the various parameters involved in the problem. However, one cannot expect to reduce the entire fire propagation modelling problem to the solution of this relatively trivial—albeit important—case. As will be shown below, the propagation of each element of the fire line will depend not only on local range conditions, but on its interaction with neighbouring elements and also, within certain limits, on the overall shape of the fire front.

(*h*) *Deterministic and statistical approaches*

In the above considerations a deterministic approach to the problem was made, in the sense that it was assumed that the state of present knowledge allowed us to define the required boundary conditions, to establish the governing equations and to find the solution of the problem. Given the uncertainties associated with many of the variables and even with some of the processes involved, some authors (see, for example, O'Regan *et al*. 1976; Fujioka 1985; Von Niessen & Blumen 1986, 1988) drop one or more of the deterministic points of view and make a so-called statistical approach. There are various levels of statistical modelling of fire propagation, from those that assume a random description of the fuel cells' properties and of the meteorological parameters, namely wind variation with time, to those that use a deterministic description of the fuel cells, but consider random variation of the wind flow around a certain average value. This type of model has been used for simulation purposes, to design possible or probable fire spread scenarios, but in the opinion of the present author they may also give interesting qualitative and quantitative insight to the problem, and can be particularly useful when large uncertainties about input data exist.

3. Convection effects

(*a*) *Effect of slope*

In order to illustrate the relevance of buoyancy-induced convection flows even in relatively small fires, we shall now analyse the observations made in a series of

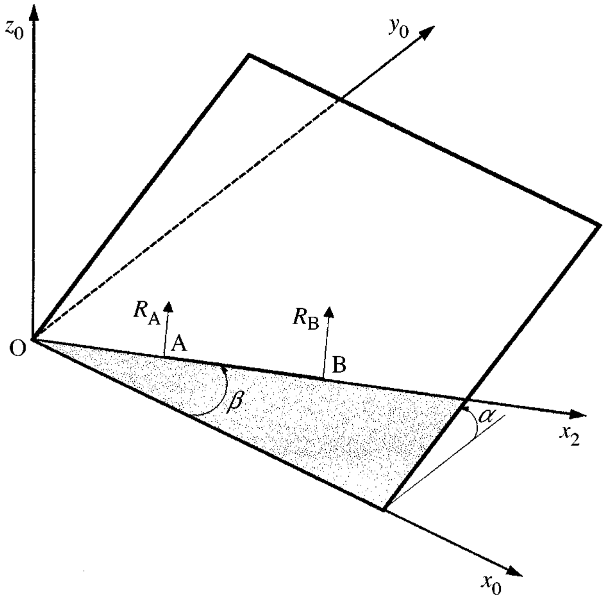

Figure 3. Definition of inclination angle β of a linear fire front in a slope inclined at an angle α in relation to the horizontal datum.

laboratory experiments in which a linear fire front is propagated in a plane slope. These experiments will also show that segments of non-uniform fire fronts cannot be treated as independent parts of the fire's perimeter.

Details of the experimental set-up can be found in Viegas (1998). The combustion table had a platform of 1.6 m × 1.6 m, that could be inclined in the range $0° < \alpha < 40°$, with a 5° interval. The platform could also be rotated around a perpendicular axis so that one of its edges could make an arbitrary angle β with a horizontal line in the platform plane (figure 3). The angle β could be varied by steps of 5° in the range $0° < \beta < 180°$. In this form, for a given slope angle α of the platform plane, a straight fire line with arbitrary inclination β could be started at the edge of the platform. Still pictures at predefined time-steps were taken from each test by a photographic camera placed above the table with its optical axis perpendicular to the platform. From these pictures the evolution of the fire line during each test could be analysed. The fuel bed consisted of pine needles with the same properties as those used in the tests reported in figure 1; particular care was taken to create a uniform fuel layer and to avoid extraneous air movements in the vicinity of the table. Each experiment was repeated several times, in order to minimize errors due to non-controlled parameters. The moisture content of the fuel particles used in the tests varied in the range $10\% < m_{\mathrm{f}} < 16\%$. In this paper only results from experiments made with a slope angle $\alpha = 30°$ are reported, although other values of α were also tested with similar results.

The rate of spread R_1 of a linear fire front spreading on a slope of angle α varies typically according to the distribution shown in figure 4, which was obtained from tests performed in the combustion table described above. In this figure, the rate of spread is rendered non-dimensional by dividing its value by the basic rate of spread R_0 defined above. As can be seen for negative values of α (downslope-propagating

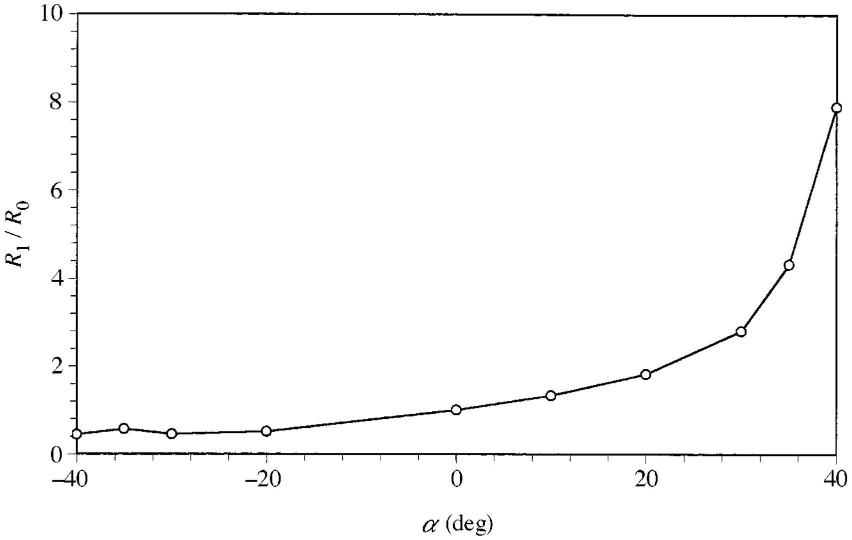

Figure 4. Non-dimensional rate of spread R_1/R_0 of a linear fire front in a slope, as a function of the slope angle α. Laboratory experiment with a fuel bed made of dead needles of *Pinus pinaster*, the fuel bed was 1.6 m × 1.6 m with a height of 7 cm.

fires), the rate of spread is slightly less than R_0, and it is practically constant, while for upslope-propagating fires the ratio R_1/R_0 can reach a value of the order of ten on this scale. Similar results are reported by other authors for different types of fuel beds (Rothermel 1972; Van Wagner 1977*b*; Dupuy 1995).

In the previous experiments the fire line was initially horizontal, the rate-of-spread $\boldsymbol{R}$ and slope $\boldsymbol{S}$ vectors being parallel. Let us see now what happens to a fire line that is inclined so that its normal $\boldsymbol{n}$ ($\boldsymbol{n} \parallel \boldsymbol{R}$) makes an angle β with the slope gradient $\boldsymbol{S}$.

A typical sequence of photos for a test performed with an initial inclination $\beta = 30°$ is shown in figure 5. The lower edge of each photo coincides with the initial position of the fire line and it is therefore inclined at $\beta = 30°$ in relation to a horizontal reference line in the plane of the fuel bed. As can be seen in this figure, after an initial period of fire development, in which the flame height is relatively uniform, the flame height increases from the bottom of the fire line to its top (from right to left in each photo). This increase is due to the transport of heat across the fire line, caused by the vertical convection induced by the flame. From simple geometrical properties it is easy to see that this convective flow can be split in two components, one perpendicular to the fire front and one parallel to it. The latter is responsible for the already mentioned flux along the fire front and for the non-uniformity of the flame surface.

As a consequence of the non-uniform radiation field across the fire front, a substantial part of it begins to rotate, tending to become parallel to the slope gradient ($\boldsymbol{R} \perp \boldsymbol{S}$). In the other part of the fire front, the head tends to become horizontal ($\boldsymbol{R} \parallel \boldsymbol{S}$). If we analyse the movement of the main part of the fire line we can observe that between time-steps t_1 and $t_1 + \Delta t$, the inclination angle of a given element of this fire line varies between β_1 and $\beta_1 + \Delta\beta$. We can therefore define an angular velocity of rotation ω of the element of fire line by $\Delta\beta/\Delta t$. For a given fuel bed, ω will be a function $\omega(\alpha, \beta)$ of both α and β. In order to suppress the dependence

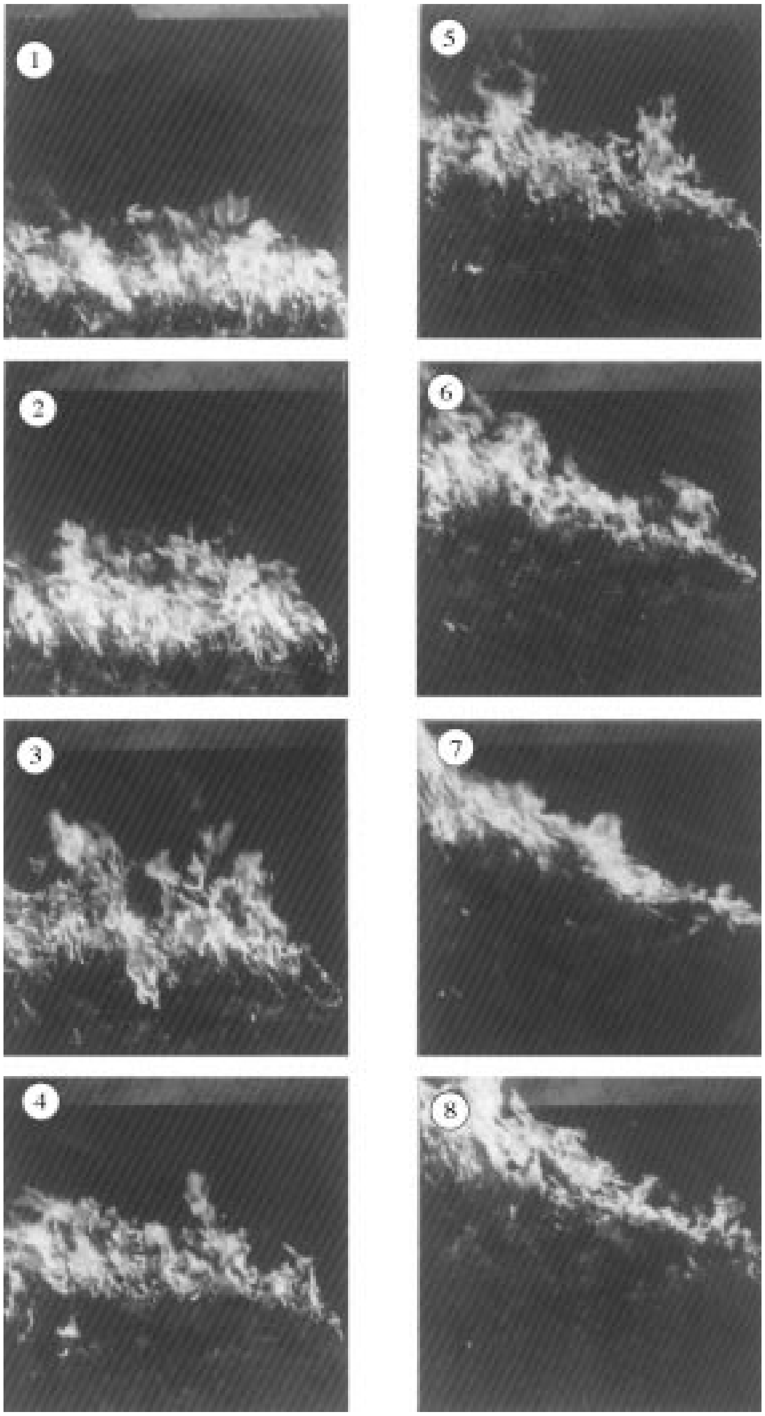

Figure 5. Sequential photos of the evolution of a linear fire front with an initial inclination $\beta = 30°$, on a slope $\alpha = 30°$. The time-interval between the photographs is 15 s and the experiment was held under the same conditions as in figure 4.

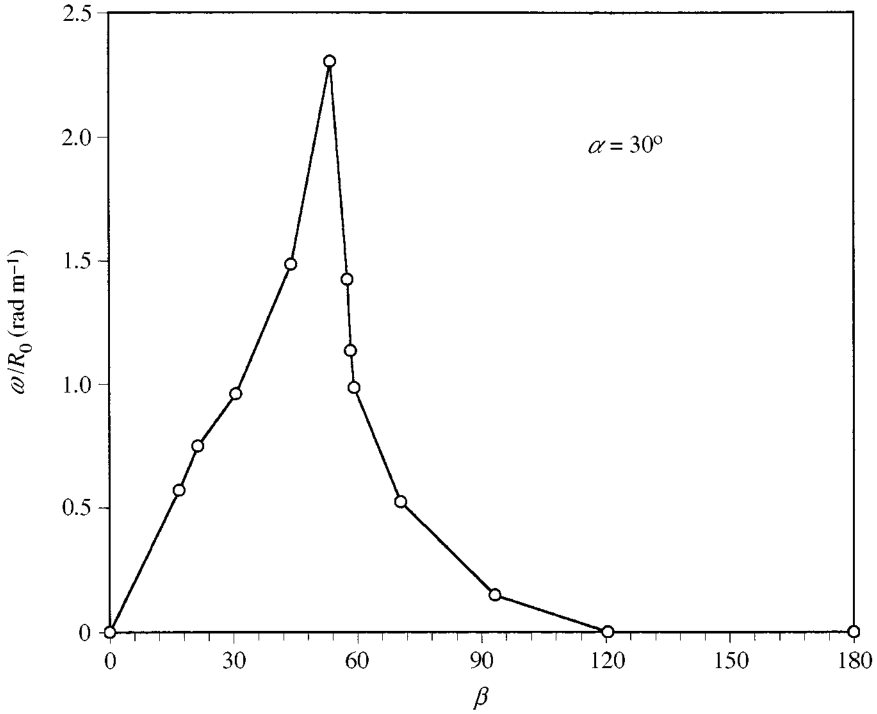

Figure 6. Relative angular velocity of rotation ω/R_0 of a fire line element in a 30° slope as a function of its inclination angle β. Average values from a series of experiments performed in the same conditions as in figure 4.

on the fuel bed properties, we shall divide the rotational speed by the basic rate of spread R_0, of the fuel bed, for no-wind and no-slope conditions: $\omega' = \omega/R_0$. The results obtained in a series of tests for $\alpha = 30°$ are shown in figure 6. As can be seen, ω' is zero for $\beta = 0°$, as required by symmetry conditions, then it increases up to a maximum for β values of around 60°, and afterwards it becomes practically null for $90° < \beta < 180°$. Similar results were obtained for other values of α.

From the above described results the following conclusions can be drawn.

(1) For $\beta = 0°$ or $\beta = 180°$ we have an equilibrium fire propagation condition, in the sense that an upward or downward propagating fire will remain parallel to itself. Nevertheless, it must be noted that $\beta = 0°$ corresponds to an unstable regime, as any non-uniformity in the environment will induce local rotations of the fire front and the tendency to form the so-called fingers, or convex protrusions, of the fire front into the non-burned fuel.

(2) For values of $0° < \beta < 90°$, the propagation of the fire line element is composed of a translation and a rotation, whose properties change continuously with the value of β; as no stable fire spread can be achieved in these conditions, it makes no sense to characterize its movement by a translation rate of spread, the use of an angular rotation seeming to be more appropriate.

(3) For $90° < \beta < 180°$, i.e. for fire lines propagating with a downward component, the fire line will propagate with practically zero rotation and stable propagation will occur, the corresponding rate of spread $\boldsymbol{R}$ being almost equal to R_0.

We can use the laws $R_1(\alpha)$ and $\omega(\alpha, \beta)$ determined experimentally to evaluate the translation and rotation of a generic element of a generic fire line element. With this procedure the evolution of the fire line can be estimated numerically.

The concept of fire line rotation can be applied, with some simplifying assumptions, to the interpretation of the evolution of a fire started at a single point on a slope, and used to explain the modification in its shape from an initial circle to an elliptic-like form. The permanent and uniform conditions for performing such a test can only be achieved in the laboratory. An example of a test performed on the same table for $\alpha = 30°$ is shown in figure 7 as a sequence of photos taken at 15 s intervals.

The head of the fire will propagate at a rate equal to R_1, while the back of the fire will propagate at a rate practically equal to R_0. If we consider an arbitrary element of the fire line, at a given time-step t_1, knowing its local value of β, the corresponding value of ω' can be obtained from figure 6, assuming that the law derived for a relatively long linear fire front is applicable to a small element of a curved fire line. The result of this calculation is given in figure 8 for the same case. This computation shows that in its evolution the fire front is always changing its shape: the flanks of the fire tend to become straight lines almost parallel to the slope gradient and a horizontal head fire is formed; the rear of the fire is the only part of the fire that can be easily approximated by a segment of an ellipse. The inclination angle of the flanks is related to the angle β for which $\omega \approx 0°$.

The above-described experiments, involving only slope effect were performed in the laboratory, under carefully controlled conditions. It is virtually impossible to perform these experiments in the open field, due to the presence of wind. In spite of the relatively small scale of the experiments, the mechanisms that were described are also found in real situations, and they are enhanced by the presence of wind, as was observed in laboratory tests and also in real fire situations. The laws describing the fire line rotation $\omega(\alpha, \beta)$ found in the laboratory may not be applicable accurately to field cases, but in qualitative terms the observed mechanisms are the same.

(b) *Effect of wind*

Wind has an effect on fire spread similar to that described for slope-induced convection, the difference is that it can be much more intense. For example, a wind-driven fire may propagate at a rate of spread about 100 times or more greater than its rate in no-wind conditions, while the corresponding slope effect does not exceed a factor of 20. Besides this, wind is much more effective in porous fuel beds, while the slope-induced effect is not as sensitive to fuel bed porosity (Rothermel 1972).

For the same fuel bed of *Pinus pinaster* dead needles that was used in the slope experiments, the effect of wind on the rate of spread as a function of wall shear stress τ_w is shown in figure 9. These experiments were performed in the combustion tunnel at the University of Coimbra, which has a useful length of 8 m and a width of 3 m. The rate of spread with favourable wind (positive τ_w) and with contrary wind is shown. The basic rate of spread R_0 was equal to $0.22\ \mathrm{cm\,s^{-1}}$ in these tests.

If the wind velocity is not aligned with the rate of spread direction, a situation similar to that described above is obtained. In this case the wind velocity $\boldsymbol{U}$, or some equivalent parameter like $\boldsymbol{u}_\tau$, will take the place of α as an independent variable, the other variable being the angle β between $\boldsymbol{U}$ and $\boldsymbol{R}$. Experiments performed by the author in the combustion tunnel with oblique fire fronts ($\beta \neq 0°$) and various

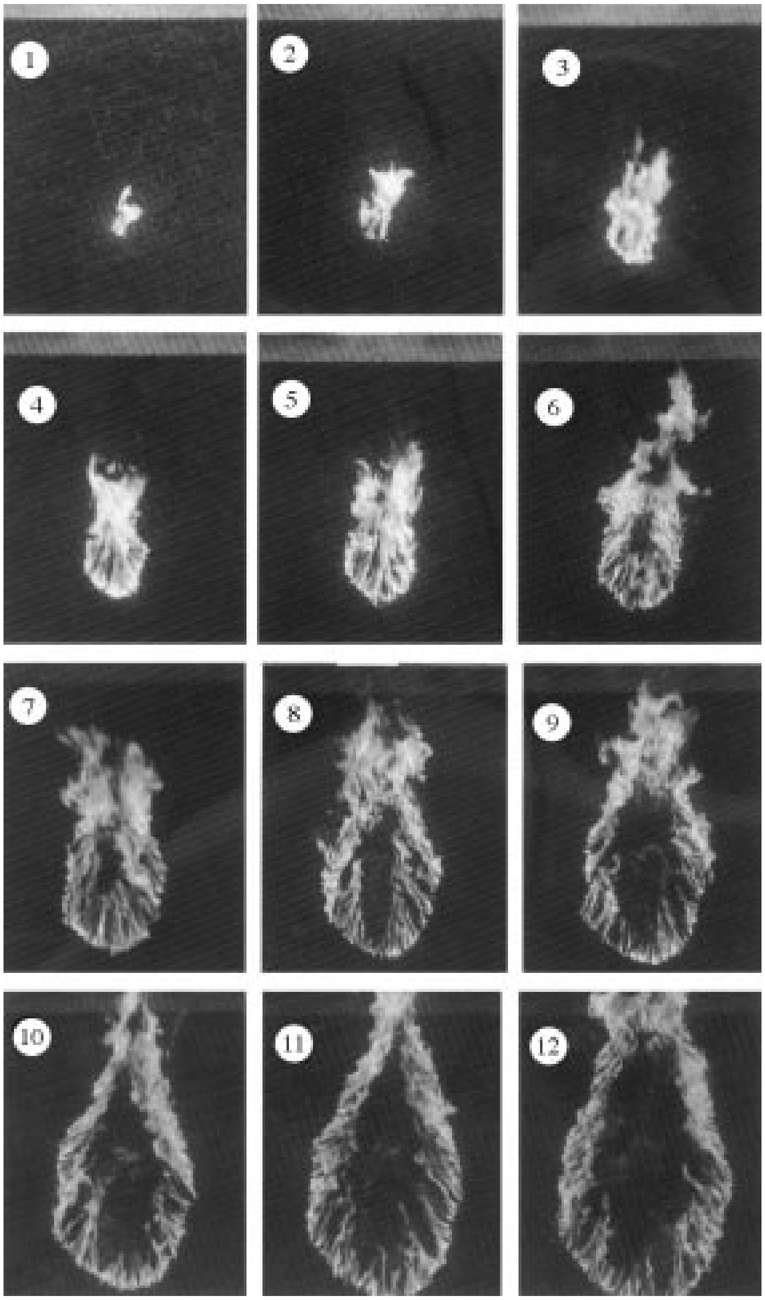

Figure 7. Sequential photos of the evolution of a circular fire front on a slope $\alpha = 30°$. The time-interval between photos is 15 s. Same conditions as in figure 4.

wind velocities in controlled conditions confirmed this remark. Observation of the evolution of real fires and of the final shape of some past wind-driven fires (Taylor & Williams 1967; Wade & Ward 1973; Anderson 1983; Pyne 1984) also provides evidence to support this interpretation of the fire front evolution.

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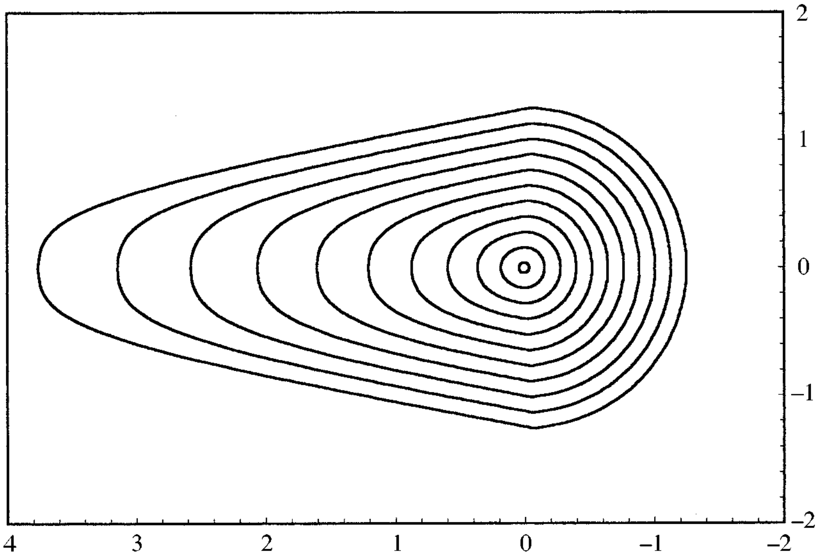

Figure 8. Numerical prediction of the evolution of a circular fire front on a 30° slope. The basic rate of spread is $R_0 = 0.22\ \text{cm s}^{-1}$ and the time-interval between lines is 60 s (distance units are in metres).

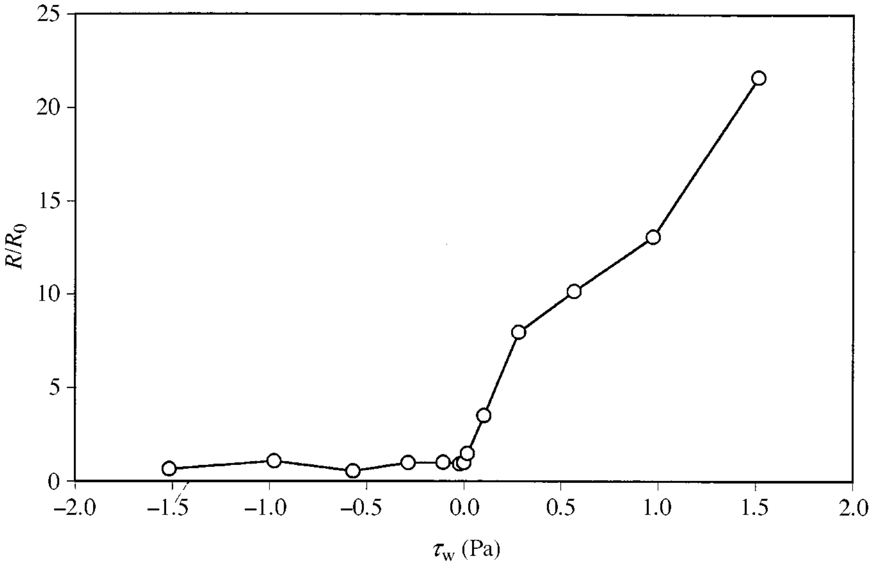

Figure 9. Non-dimensional rate of spread R_1/R_0 of a linear fire front in a boundary layer flow as a function of the average wall shear stress τ_w. Combustion tunnel experiment with a fuel bed made of dead needles of *Pinus pinaster*; the fuel bed is $2.6 \times 8\ \text{m}^2$ with a height of 7 cm.

(*c*) *Global fire front spread*

In the prediction of the global evolution of a fire front, quite often there are situations in which wind and slope effects are both present simultaneously. It is therefore necessary to determine the main forward propagation direction of the fire both at a global and at a local range. Some sections of the fire front may be controlled by local terrain or vegetation features—a ridge, or a drastic change in the vegetation cover, for example—while others are dominated by the overall fire. To solve the local range problem, Rothermel (1983) proposed a vector sum of the wind and slope effects. In spite of the limitations of this solution it embodies the concept of a relationship between the buoyancy-induced convection and the wind-forced convection that is consistent with our observations. The head of the fire will propagate along this main direction, while the remaining part of the fire front will either spread backwards ($\beta > 90°$) or will rotate, tending to become parallel to the main direction. If there is a change of topography or wind conditions, the fire front will adapt itself to the new situation. In most cases these changes occur so frequently that the process of fire line rotation is not completed and therefore the shape of the fire can be reasonably assimilated to an ellipse. Therefore the predictions based on this shape provide an accuracy that is acceptable for most practical applications, especially taking into account the uncertainties that still exist in the entire fire behaviour prediction process.

One terrain configuration that is particularly important is that of a ridge or a canyon, formed by the intersection of two slopes creating a chimney. Lopes *et al.* (1995) developed a numerical model to solve the turbulent flow and the fire spread for this case. Very high rates of spread induced by the chimney effect were obtained in this terrain configuration, which is consistent with field observations.

Besides the interaction of the terrain configuration and the spreading fire, one interesting problem analysed in this study is that of the interaction of the fire and the wind field itself. Taking into consideration the buoyancy-induced flow and its modification to the main wind field, Lopes *et al.* (1995) found that much higher values of the rate of spread of the fire were obtained for the same conditions assuming a non-disturbed wind field. This is a subject of current investigation as extensive and reliable field data are not available to validate existing models of fire spread, particularly for these complex situations.

4. Conclusion

The main fire development phases and forest fire propagation regimes have been characterized, and the factors that affect them described. Difficulties associated with the problems of modelling fire propagation have been addressed, both at local and at global ranges. The very important role played by natural and forced convection and by radiation in flaming fire spread was discussed. From a set of laboratory experiments on the propagation of an inclined linear fire front in a slope it was shown that whenever there is an upslope component in the movement of the fire front the fire tends to rotate, until an equilibrium orientation is reached. It is inferred that the same mechanism applies to wind-driven fires. The concept of fire line rotation can be used as a tool to interpret and to describe the overall movement of a fire front in arbitrary conditions.

The author thanks all his colleagues and research students that contributed to the body of results and thought that is expressed in this article. The support given by the Science Foundation (JNICT) of Portugal, by the European Union and by several private and public institutions to the research programme that was carried out at the University of Coimbra is also gratefully acknowledged.

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