Fire Spread in Canyons

by

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Abstract

Canyons or ridges are associated to a large number of fatal accidents produced during forest fires in the past, all over the World. A contribution to the understanding of fire behaviour in these terrain conditions is given in this paper.

The basic geometrical parameters of the canyon configuration are described. An analytical model assuming elliptical growth of point ignition fires and constant values of rate of spread is proposed. A non-dimensional formulation to transfer results from analytical, numerical, laboratory or field simulations to other situations is proposed.

An experimental study at laboratory scale on a special test rig is described. A wide set of canyon configurations were covered in the experimental program. In spite of the relatively small scale of the experiments they were able to put in evidence some of the main features found in fires spreading in this type of terrain. They show that in practically all cases the rate of spread of the fire front is non-constant. On the contrary the fire has a dynamic behaviour and its properties depend not only on the canyon geometry but on the history of fire development as well. The convection induced by the fire is enhanced by terrain curvature and the fire accelerates causing the well-known blow up that is associated to canyon fires. The rate of spread of the head fire increases continuously even in the absence of wind or any other special feature or change of the boundary conditions that are sometimes invoked to justify such fire behaviour.

The results of the present study confirm the predictions of a previous numerical study of the flow and fire spread in canyons that showed the important feedback effect of the fire on the atmospheric flow and how this affected fire behaviour in canyons.

Results from a field experiment carried out in a canyon shaped plot covered by tall shrubs were used to validate the laboratory scale experiments.

Case studies related to fatal accidents that occurred in canyon shaped configurations are analysed and recommendations to deal with this problem are made. It is shown that these accidents may occur even in the absence of special fuel or atmospheric conditions as they are intrinsically related to terrain configuration.

Key words: Fire behaviour; Canyons; Fire dynamics; Blow-up; Convection effects; Chimney effect.

Summary:

A mathematical model, including a non-dimensional analysis of the spread parameters to interpret fire spread in canyon shaped geometry is proposed. Experimental results from an extensive laboratory study and from one field experiment support the relevance of the terrain configuration on the fire spread properties. It is demonstrated that fire behaviour in canyons is dynamic.

1 Introduction

Canyons or ridges are associated to a great percentage of fatal accidents produced during forest fires in the past, all over the World. The chimney effect created by this topographic configuration induces a sudden and very fast propagation of the fire that has surprised even some very experienced fire fighters and caused many losses of lives.

In spite of the relevance of this terrain configuration in practical terms, namely in the very important fire safety area there are very few systematic studies about this topic. There are many references to fires in canyons in the literature but these authors did not find any detailed and quantified analysis of fire spread in this terrain feature. Most references give only qualitative but otherwise very useful descriptions and insight to the extreme fire behaviour that occurs in canyons. An overview of some well known basic texts on forest fires is given below in order to present the state of the art as it is expressed in the literature known to these authors.

Brown and Davis (1959) give a very good qualitative description of fire behaviour in general. They mention the important role of wind and topography and describe the behaviour of a fire in a steep slope or a ridge. They make a very interesting and important distinction between the roles of slope or wind that is sometimes overlooked. In the section of high-energy fires they define the phenomena of blow-up and the transition from a low energy to a high-energy fire. According to these authors this transition is seldom a gradual process and it is usually the result of a conjunction of factors like a pick-up in wind speed, start of crowning or a rapid growth of numerous spot fires.

Pyne (1984) gives also a very good description of forest fire phenomena, namely of the factors affecting fire behaviour. He mentions that deep narrow canyons are likely to burn like a unit due to radiation and fire-brand emission from one side to another. Pyne says that deep canyons encourage the formation of convective columns that act as chimneys, channelling heat into narrow funnels. As a result the convection velocity increases and, with it, the rate of combustion. Pyne also mentions that a number of fire casualties have occurred from fire behaviour dominated by topographic factors such as steep slopes and ridges. In its chapter on fire suppression Pyne presents some selected cases of fire fatalities. Among them the Loop Fire, 1966, and the Battlement Creek Fire, 1976, occurred in canyons.

In their chapter on fire behaviour Chandler et al. (1983) describe the development of a fire from a point source and refer two acceleration phases, the second one corresponding to transition to large fire behaviour. According to these authors this transition can be caused either by pseudo-flame front formation by spot fires or due to topography. The latter possibility is illustrated by the case of a fire entering the mouth of a drainage basin with a strong up-canyon wind. The fire runs up-canyon pushed by the wind but slope effects causes the fire to burn rapidly to the ridge crests on both sides. The result is very rapid involvement of the entire drainage.

Pyne et al. (1996) in part one of their book, dealing with fire environment, mention that narrow canyons or ravines can affect fire behaviour in several ways. Radiation from one slope to another and sparks or embers may cause a whole slope to ignite in a matter of few minutes. The existence of a thermal inversion is also mentioned as a factor to increase fire activity.

Velez et al. (2000) in chapter 8.2 dealing with the influence of topography on fire behaviour indicate that terrain slope is a most important factor in fire behaviour. These authors consider that canyons or ridges with closely spanned faces create adequate conditions for fast fire spread due to pre-heating of fuels ahead of the flames.

It is easy to recognize that the common idea behind quick fire growth in canyons is related essentially to secondary effects like preheating of fuel well ahead of the fire front, the projection of fire embers and even on the existence of thermal effects on the atmosphere, like a thermal inversion. The central role of terrain slope and configuration is not put in evidence.

The only previous work known to the authors dedicated to the study of canyon fires is Lopes (1994) who carried out a numerical study about fire spread in canyons using complete physical equations to model turbulent air flow and its interaction with the heat source created by the fire. Two different fuels and various geometrical configurations were analysed. The flow acceleration created by canyon configuration and the radical increase on rate of spread and general fire behaviour considering wind-fire interaction were demonstrated for the first time. These results were also reported in Lopes at al. (1995). This work is analysed more in detail later in this paper.

In forest fire behaviour studies quite often much attention is devoted to radiation from the flame front as the dominating process in fire spread. The role of convection induced by the fire, eventually enhanced by terrain configuration and its interaction with the combustion process and the fire front shape is sometimes overlooked, making it difficult to explain some features that are observed in forest fire propagation in complex terrain, like in the case of a canyon.

The basic geometrical parameters of the canyon configuration are described. The effects of slope and wind on fire spread are revised putting in evidence the role of fire-induced convection.

Comparison with the results of a numerical study of the flow and fire spread in canyons that show the important feedback effect of the fire on the atmospheric flow and how this affects fire behaviour shall be presented.

2 Canyon Geometry

Canyons are a relatively common topographical feature in complex terrain. Without great loss of generality we will assume that the terrain surfaces are plane surfaces, i.e. without any curvature. Therefore we consider a canyon as the space above three planes intersecting at given angles. The base of the canyon is a horizontal datum plane P_0 and the faces of the canyon are two other planes P_a and P_b that are inclined in relation to the horizontal. In analogy to what happens frequently in Nature the intersection line of the two faces of the canyon will be designated as the water line. The general form of a canyon is a non-symmetrical canyon that is represented schematically in figure 1.

It is easy to see that the canyon can be generated in two steps:

(i) Firstly we consider two planes P_a and P_b that intersect along axis OY_o and make initially an angle δ_1 and δ_2 with the reference horizontal plane OX_oY_o.

(ii) Secondly if the dihedral formed by both planes is inclined until their intersection line – the water line - makes an angle α with the horizontal plane the symmetrical canyon that is presented in figure 1 is formed.

In this figure the water line is the OY_1 axis of a new reference frame that is obtained from the basic $OX_oY_oZ_o$ by a rotation of the angle α around axis OX_o. As these two movements, defined by angles α, δ_1 and δ_2 are sufficient to generate and characterize the canyon geometry we shall use these three angles as basic canyon geometry parameters in the present study.

For practical purposes it is important to identify a set of additional angles that can be used in complement to α, δ_1 and δ_2. These angles are θ, ϕ and ψ that are shown in figure 1 for plane P_a and are defined in Table 1.

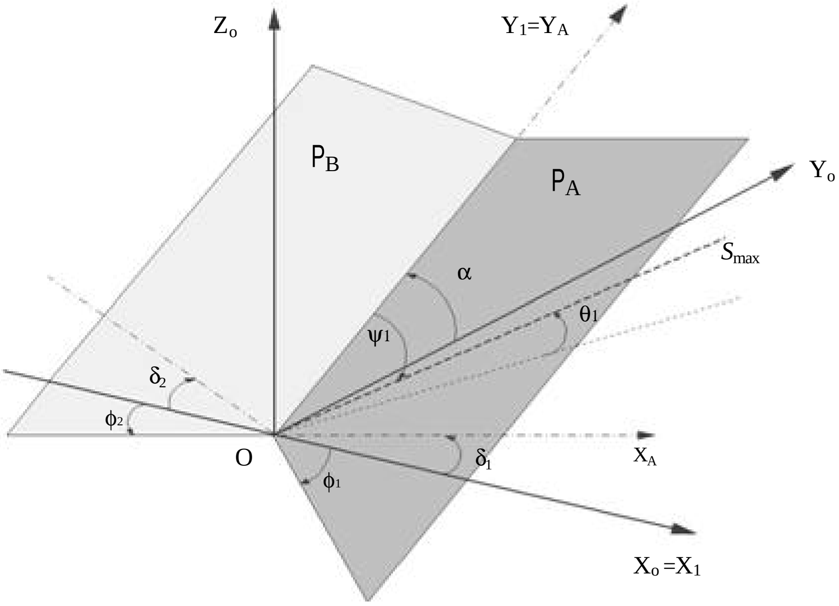


Figure 1 – Definition of the geometry of a non-symmetrical canyon.

Table 1 – Nomenclature of Canyon Geommetry

Designation	**Definition**
$O\ X_oY_oZ_o$	Orthogonal basic reference
$O\ X_oY_o$	Reference horizontal plane (Plane P_0)
OX_1Y_1	Inclined reference plane (Plane P_1)
OX_AY_A	Right face of the canyon (Plane P_a)
OX_BY_B	Left face of the canyon (Plane P_b) (Axis OX_B is not marked in the figure)
S_{max}	Line of maximum slope in face OX_AY_A
δ_1	Angle between axis OX_o and OX_A
δ_2	Angle between axis OX_o and OX_B ($\delta_1=\delta_2=\delta$ for symmetrical canyon)
α	Angle between axis OY_o and OY_1
θ	Slope of canyon faces (angle between S_{max} and the horizontal plane)
ϕ	Angle between OX_o and the intersection of each face with horizontal plane OX_oY_o
ψ	Angle between OY_1 and the maximum slope direction of each face

As the symmetrical canyon is the main situation that will be considered in the present work the following description and definitions pertain only to this case.

With some mathematical manipulation it can be demonstrated that the following relationships exist between angles θ, ϕ and ψ and the two basic angles α and δ. The graphical form of those functions is presented in figures 2, 3 and 4.

$$\tan\theta = \frac{\sqrt{\sin^2\alpha + \tan^2\delta}}{\cos\alpha} \qquad [1]$$

$$\tan\phi = -\frac{\tan\delta}{\sin\alpha} \qquad [2]$$

$$\tan\psi = \frac{\cos\delta + \cos\alpha.\sin\alpha.\cos\delta + \sin\alpha.\tan\delta - \sin^2\alpha.\cos\delta}{\dfrac{\sin\alpha}{\tan\delta} + \dfrac{\sin^2\alpha}{\tan\delta} + \dfrac{\sin^2\alpha}{\cos\alpha.\cos\delta}} \qquad [3]$$

As can be observed in figures 2, 3 and 4 for each pair of values of α and δ there is a single value of each other angle, ϕ, θ and ψ, but the reciprocal is not true. For example there are different pairs of values of α and δ that correspond to the same value of θ or ψ.

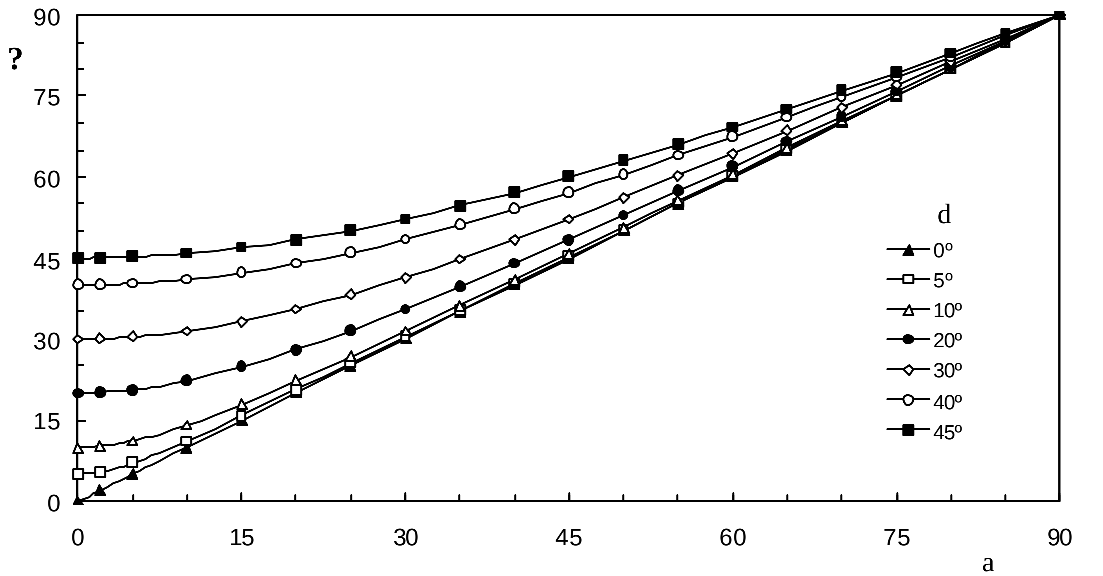


Figure 2 – Slope θ of each face of the canyon as a function of α and δ.

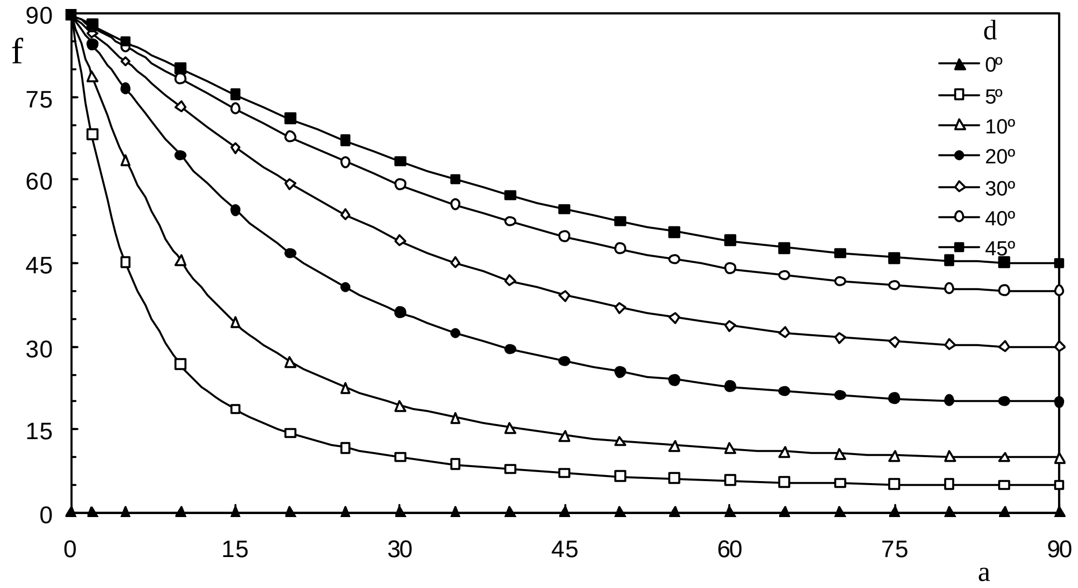


Figure 3 – Modulus of angle ϕ between OX_0 axis and the trace of each face of the canyon on the horizontal plane, as a function of α and δ.

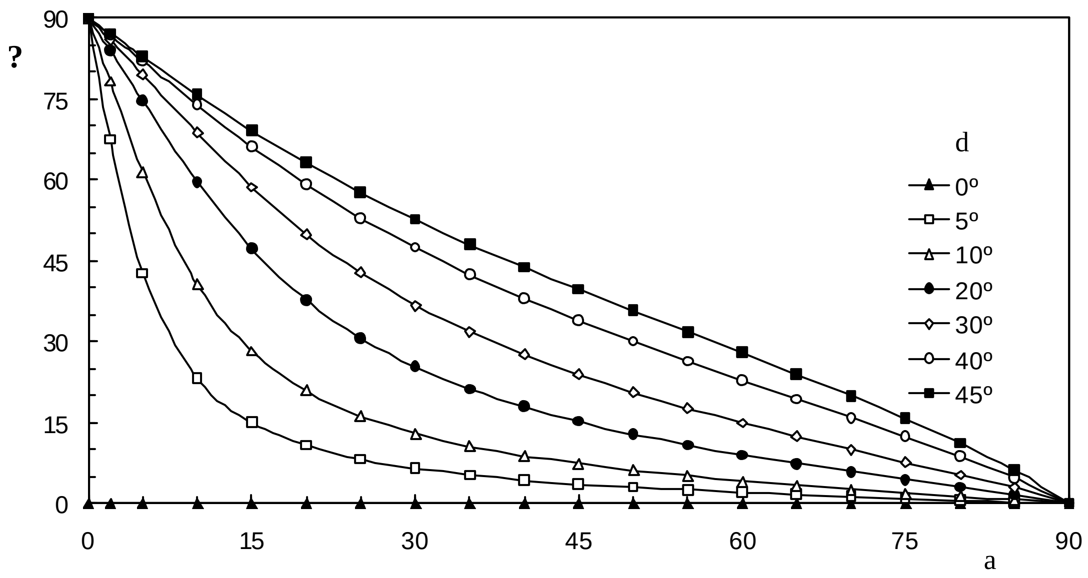


Figure 4 – Angle ψ between OY_1 axis and the direction of maximum slope of each face of the canyon, as a function of α and δ.

A non-symmetric canyon can be obtained making δ_1 ? δ_2. The equations to determine the geometry in this case are the same as the ones presented here although they have to be applied to each face of the canyon using the appropriate value of δ. As this case is not dealt with in this paper we do not give the corresponding equations here.

Our experimental program did not cover the case of the non-symmetrical canyon yet but it is anticipated that this situation is not just the addition of two cases as fire spread in both faces of the canyon are not independent of each other.

3 Fire Spread Modelling

3.1 Fire spread parameters

The fire spread properties will be dependent on the following parameters:

- Canyon geometry
- Fuel cover
- Wind flow
- Ignition pattern.

In this paper we are looking in particular to the effect of canyon geometry on fire spread, therefore only very simple situations related to all the other parameters shall be considered.

Fuel cover will be assumed to be uniform and with homogeneous properties in the entire canyon.

We will consider mainly the case of no wind although a reference will be made to a model that includes wind flow as well.

Ignition will be assumed to be at a single point in the line of symmetry of the canyon and near its base, i. e. slightly above the origin of the reference axis.

In this paper we shall deal mainly with the local rate of spread and with the overall shape of the fire. Therefore only kinematical parameters like the ones described below shall be dealt with. It is obvious that other related properties like flame length or fire line intensity may be derived from these ones for given fuel cover conditions.

3.2 Analytical model

A simple analytical model to estimate the shape and size of the fire in symmetric canyons is presented here. This model is not proposed as a fire behaviour predictor in a canyon. Its purpose is only to serve as a reference and to put in evidence the limitations of present state of the art fire behaviour models based on the concepts of elliptical fire growth and constant rate of spread. Comparing the results of this model with the experimental measurements we shall see the importance of fire dynamics induced by convective flow around the fire front and its interaction with the reactive fire front. As a corollary we shall conclude that fire behaviour prediction using a constant rate of spread is not at all correct in the present case.

As the driving force of the fire is the terrain slope we have to determine its maximum gradient angle θ (eq. [1]) and estimate the rate of spread of the head fire along this direction. In the presence of a slope of inclination θ the upslope and down-slope rate of spread of the fire line, parallel to the slope plane, is given respectively by:

$$\boldsymbol{R_1} = f_1 . \boldsymbol{R_o} \quad [4]$$

$$\boldsymbol{R_2} = f_2 . \boldsymbol{R_o} . \quad [5]$$

In these equations $\boldsymbol{R_o}$ is the basic rate of spread of a linear fire front on a horizontal fuel bed in the absence of wind. $\boldsymbol{R_o}$ depends on several properties of the fuel, namely on its surface to volume ratio σ, its moisture content $\boldsymbol{m}_f$, packing ratio b (as defined in Rothermel, 1972). We assume that the value of $\boldsymbol{R_o}$ is well defined for the fuel bed and that it is known. Rothermel (1972) mathematical model provides an algorithm to estimate the basic rate of spread $\boldsymbol{R_o}$ for a wide range of fuel beds with reasonable accuracy. The value of $\boldsymbol{R_o}$ can also be obtained empirically by direct measurement as will be the case in the present study.

In principle both $\boldsymbol{f}_1$ and $\boldsymbol{f}_2$ are a function of θ, but we can assume that for down slope propagation $\boldsymbol{f}_2$˜1 as an approximation.

For convenience in this study we shall use an empirical law obtained in this work for one of the fuel beds (*Pinus pinaster* needles) that was more extensively used (cf. figure 17.b)).

$$\boldsymbol{f}_1 = 1 + a_1.\theta + a_2.\theta^2 + a_3.\theta^3 + a_4.\theta^4 \quad [6]$$

The values of the constants are $a_1 = -0.0175$, $a_2 = 0.0039$, $a_3 = -0.0001$, $a_4 = 3 \times 10^{-6}$ and this equation is valid for $0 < \theta < 55°$.

In the absence of wind the only factor affecting the rate of spread will be the local slope θ of the fuel-bed. For point ignition fires according to some authors the fire will evolve like a simple or double ellipse with its major axis aligned with the slope gradient direction of the terrain.

We shall use a double ellipse model shown in figure 5.

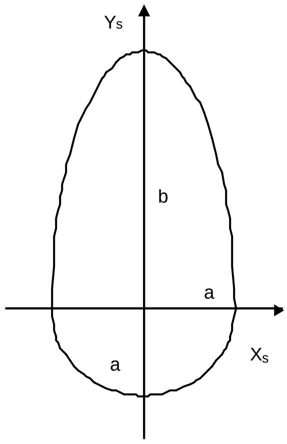


Figure 5 – Double ellipse propagation model.

The equations of the double ellipse in the OX_sY_s plane depicted in figure 5 are:

$$a=\boldsymbol{f}_2.\boldsymbol{R}_o.t \qquad [7]$$

$$b=\boldsymbol{f}_1.\boldsymbol{R}_o.t \qquad [8]$$

$$\begin{aligned} y_s > 0 \Rightarrow y_s &= \frac{b}{a}\sqrt{(a^2 - x_s^{\,2})} \\ y_s < 0 \Rightarrow y_s &= \frac{a}{a}\sqrt{(a^2 - x_s^{\,2})} \end{aligned} \qquad [9, 10]$$

If the line of maximum slope has an inclination ψ in relation to OY_1 axis we have the following transformation of coordinates between both systems OX_1Y_1 and OX_sY_s:

$$\begin{aligned} y'_1 &= y_s \cos\psi - x_s \sin\psi \\ x_1 &= x_s \cos\psi + y_s \sin\psi \end{aligned} \qquad [11, 12]$$

In this equation $y'_1=y_1-y_{ig}$, y_{ig} being the distance between the ignition point and the origin of the coordinate system O_o. In the present experiments y_{ig}=0.50m.

Knowing the reference angles α and δ the values of ψ and θ can be easily determined. Knowing the value of $\boldsymbol{R}_o$ and of $\boldsymbol{f}_1(\theta)$ and $\boldsymbol{f}_2(\theta)$, using the system of equations given above it is possible to determine the shape of the fire at a given time step ***t***. It is easy to demonstrate that the shape of the fire front at a given time step depends only of ψ and of $\boldsymbol{f}_1/\boldsymbol{f}_2$. It is then be possible to determine universal shapes of the fire line for pairs of values of ψ and $\boldsymbol{f}_1/\boldsymbol{f}_2$ that could then be applied to all cases of canyon fires.

This model does not take into account the interaction of neighbour sections of the fire front. In particular it assumes that both main sections of the fire when it bifurcates do not interact in the region of the water line. As will be seen later this is a very crude assumption that is not respected in reality due to the very strong convection in that region of the fire front.

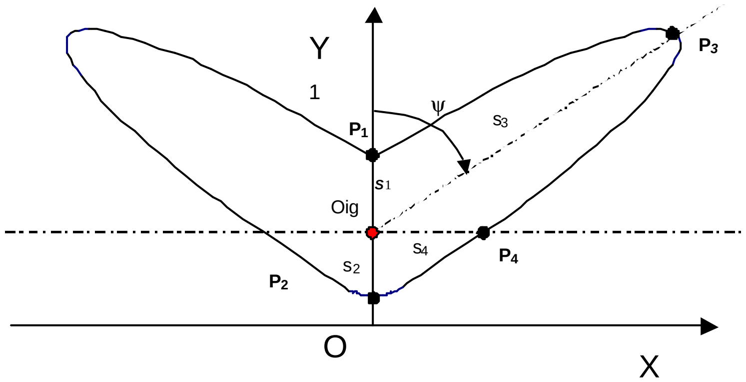


Figure 6 – Schematic presentation of fire shape given by the analytical model for a point ignition fire in a symmetric canyon

The shapes of the fire fronts given by this model for some of the 20 geometrical configurations studied in the present experimental program (see chapter 5) are given in figures 12, 13 and 14.

It is easy to derive explicit expressions to evaluate the distance from the fire origin O_{ig} to some particular points of the fire line that are illustrated in figure 6.

Table 2 – Definition of relevant points and distances for fire spread analysis

Symbol	**Definition**	**Distance from fire origin O_{ig} to:**
$\boldsymbol{s}_1$	$O_{ig}P_1$	The most advanced point P_1 in OY_1 axis.
$\boldsymbol{s}_2$	$O_{ig}P_2$	The less advanced point P_2 in OY_1 axis.
$\boldsymbol{s}_3$	$O_{ig}P_3$	The most advanced point P_3 along the major axis of the ellipse (OY_s axis)
$\boldsymbol{S}_4$	$O_{ig}P_4$	The point P_4 with $y_s=y_{ig}$ on the fire line.

$$
\begin{aligned}
s_1 &= \frac{ab}{\cos\psi\sqrt{a^2 - b^2\tan^2\psi}} = \frac{f_1 f_2 R_o t}{\cos\psi\sqrt{f_2^{\,2} - f_1^{\,2}\tan^2\psi}} \\
s_2 &= a = f_2 R_o t \\
s_3 &= b = f_1 R_o t \\
s_4 &= \frac{ab\tan\psi}{\cos\psi\sqrt{a^2\tan^2\psi + b^2}} = \frac{f_1 f_2 \tan\psi R_o t}{\cos\psi\sqrt{f_2^{\,2}\tan^2\psi + f_1^{\,2}}}
\end{aligned}
\qquad [13, 14, 15, 16]
$$

The perimeter ***P*** of the fire line is given by:

$$P = \pi(a+b) - \psi b = [\pi(f_2 + f_1) - \psi f_1]R_o t \qquad [17]$$

and the area ***A*** is given by:

$$A = (\pi - \psi)ab + \psi a^2 = \left[(\pi - \psi)f_1 f_2 + \psi f_2^{\ 2}\right]R_o^{\ 2} t^2 . \qquad [18]$$

It is found that all the above parameters, with the exception of the area, are linear functions of time. The area grows with the second power of time.

As a consequence according to this model the time derivative of the distances s_i and of the perimeter ***P*** are in principle equal to constant values.

The rate of area growth d***A***/dt is a linear function of time and it is easy to see that it is proportional to the square root of the area itself.

$$\frac{dA}{dt} = \sqrt{\frac{A}{2\left[(\pi - \psi)f_1 f_2 + \psi f_2^{\ 2}\right]}} \qquad [19]$$

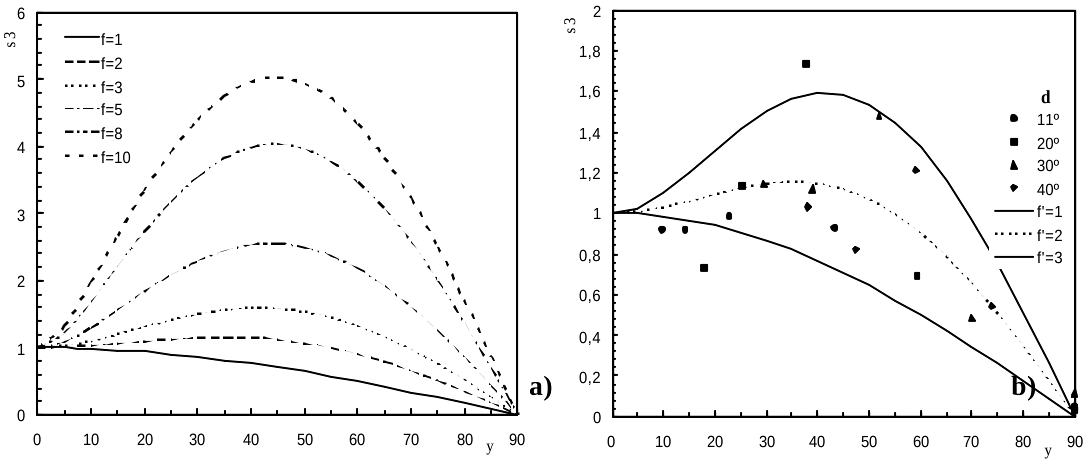
The authors observed that in canyon fires the spread of the fire along OY_1 axis tends to reach and even to overcome the advance along the maximum slope direction. This is due to the strong convection effects that occur in these fires especially near the water line. The present analytical model does not predict this effect as it does not take into account the feed back from the fire convection to the reaction zone. In order to assess the difference between model prediction and observations we introduce the following parameter:

$$\sigma_3 = \frac{s_3 \cos\psi}{s_1} \qquad [20]$$

This function is the ratio between the ***y*** component of the distance s_3 from the origin to the fire front along the maximum slope direction and the distance s_1. If $\sigma_3<1$ then the fire front advance along the OY_1 axis is greater than the OY_1 component of the fire advance along the maximum slope direction. It is easy to see that:

$$\sigma_3 = \cos^2\psi\sqrt{1 + \frac{b^2 \tan^2\psi}{a^2}} = \cos^2\psi\sqrt{1 + \frac{f_1^{\ 2}\tan^2\psi}{f_2^{\ 2}}} \qquad [21]$$

This function is shown in figure 7a) for different values of the ratio f_1/f_2. As can be seen in this figure the present analytical model predicts that in the majority of cases the fire will bifurcate and the separate heads will advance ahead of point P_1 ($\sigma_3>1$). The experimental results shown in figure 7b) confirm the trend given by equation [21] as it is illustrated by the curves for three different values of the ratio **f**= f_1/f_2 although in general the values of σ_3 are always lower than 2. In many cases they are very close to or even lower than one, showing that the head of the fire tends to propagate as a horizontal line forming a wide and devastating fire front as has been observed in some real cases. Only three experimental points are close to the line corresponding to **f**=3; according to the present experimental conditions (cf. 15.a)) the normal values of **f** are larger than 3.



(a) (b)

Figure 7 – Analysis of ratio of fire advance along maximum slope angle and the water line of the canyon (OY_1 axis). (a) Analytical model; (b) Experimental results.

3.3 Non dimensional parameters

We now address the problem of deriving non-dimensional parameters related to the fire behaviour descriptors in order to be able to compare results obtained or derived in different but similar conditions or to apply results from one case to another. This question is part of a more general problem of physical modelling and physical similarity. We will only make reference to the required concepts here.

A pre-requisite of physical similarity is that there is geometrical similarity; therefore this analysis can only be applied to cases for which the canyon geometry is the same. According to the present study this requires that the values of α and δ be the same for both cases.

A second requisite is that pairs of non-dimensional parameters describing the relevant phenomena in the process are equal in both cases. The choice of these parameters has to be done with great care. As we are dealing with a thermal process and with the description of time evolution of fire position we require reference values for at least the following fundamental parameters: space and time. To characterize space we need at least a reference length or distance $\boldsymbol{L}_o$ and the same for time $\boldsymbol{t}_o$. The definition of a parameter characterizing thermal processes in fire spread may be included in one of the above parameters, considering the heat transfer is the main process driving the fire line in this physical process. This is a simplified or reduced version of non-dimensional analysis that we follow here. A more complete analysis would involve the definition of at least a third parameter characterizing heat transfer processes for each particular fuel type but this is not attempted in this paper.

As was described above the canyon configuration is defined entirely by a set of two angles (α, δ). All the other features of the canyon geometry can be derived from these ones. Therefore if we are situated far from the borders of the faces of the canyon there is not a relevant length that can be used as a reference or scale for length dimension. The same happens with a time scale that cannot be found naturally from geometrical considerations. We have then to consider properties of the fire itself to define our reference scales.

One logic parameter is the basic rate of spread $\boldsymbol{R_o}$ that is characteristic of the fuel bed. $\boldsymbol{R_o}$ is by definition the rate of spread of a linear fire front of infinite length in that same fuel bed in the absence of slope and wind.

A length scale could be defined from $\boldsymbol{R_o}$ and considering some characteristic time, like the residence time of the flames. We prefer to take the length of the flames $\boldsymbol{L_o}$ (no slope and no wind propagation) as a length scale. A characteristic time $\boldsymbol{t_o=L_o/R_o}$ can be easily derived from the other two parameters. Non-dimensional time is defined by $\boldsymbol{t'=t/t_o}$.

From these reference values the following non-dimensional parameters can be derived:

Area $$A' = \frac{A}{L_o^2} \qquad [22]$$

Area growth $$A'' = \frac{dA}{dt} \cdot \frac{1}{L_o R_o} \qquad [23]$$

Perimeter $$P' = \frac{P}{L_o} \qquad [24]$$

Perimeter growth $$P'' = \frac{dP}{dt} \cdot \frac{1}{R_o} \qquad [25]$$

Using the present analytical model it is easy to demonstrate that that we have:

$$A' = \left[\left(\frac{\pi}{2} - \psi\right) f_1 f_2 + \psi f_2 \right] t'^2$$
$$P' = \left[\frac{\pi}{2}(f_1 + f_2) - \psi f_1 \right] t' \qquad [26, 27]$$

and also that:

$$A'' = 2\left[\left(\frac{\pi}{2} - \psi\right) f_1 f_2 + \psi f_2 \right] t'$$
$$P'' = \left[\frac{\pi}{2}(f_1 + f_2) - \psi f_1 \right] \qquad [28, 29]$$

3.4 Numerical Model

3.4.1 General description

Lopes (1994) developed a numerical model for the analysis of fire spread in a canyon. A brief revision of this paper is given here. For more details one should consult the given reference of the original thesis Lopes (1994) and also Lopes et al. (1995). The full Navier-Stokes equations for turbulent flow including thermal effects were solved in order to simulate the wind over a canyon terrain with different geometric configurations. A full size symmetrical canyon with different geometrical configurations (defined by α and δ) was considered in the study. The overall size of the computation domain was of the order of 200m. Wind flow simulation considering an incoming flow of the boundary layer type showed a marked influence of the canyon shape on the flow pattern even in the absence of fire. It was found that a stagnation zone existed at the base of the canyon and that the flow accelerated upslope reaching higher velocities for more closed canyons in comparison with a simple plane slope with the same inclination.

Numerical simulation of a non-reactive heat source placed at the bottom of the canyon demonstrated a strong interaction between the wind flow and the buoyancy induced by the heat source. The wind flow was markedly modified by the heat source.

Fire spread simulation was performed using fuel cells and a Dijsktra spread algorithm. It was assumed that the angular variation of the rate of spread was such that the resulting fire shape was a double ellipse with axis defined as in figure 5.

Two different fuels were used in that work. Fuel **a** typical of herbaceous vegetation and fuel **b** similar to slash. Rothermel's model was used to determine the local rate of spread. The rate of spread at each fire line element was computed taking into account the local wind velocity and direction and the slope effect. A modified Rothermel algorithm (cf. Viegas, 2004) was used to take into account the correspondent slope and wind effects.

3.4.2 Static and dynamic models

In the simulation of fire spread a boundary layer turbulent wind flow with a velocity of 5 m/s at 10m height was used and two basic situations were considered:

(i) Static model – so called because in this it was assumed that the wind flow was not disturbed by the fire.

(ii) Dynamic model – in this case it was considered that the presence of fire and the heat that it released affected the wind flow and therefore modified fire spread.

It was found that the results of both simulations were quite different for practically all configurations: the dynamic model showed a much higher rate of fire growth than the static one as could be expected. A typical result of that simulation is shown in figure 8. In this figure the dotted lines correspond to the static model and the full lines correspond to the results of the dynamic model. Although the results of the dynamic model seemed more plausible than those of the other model at that stage there were no data to prove this.

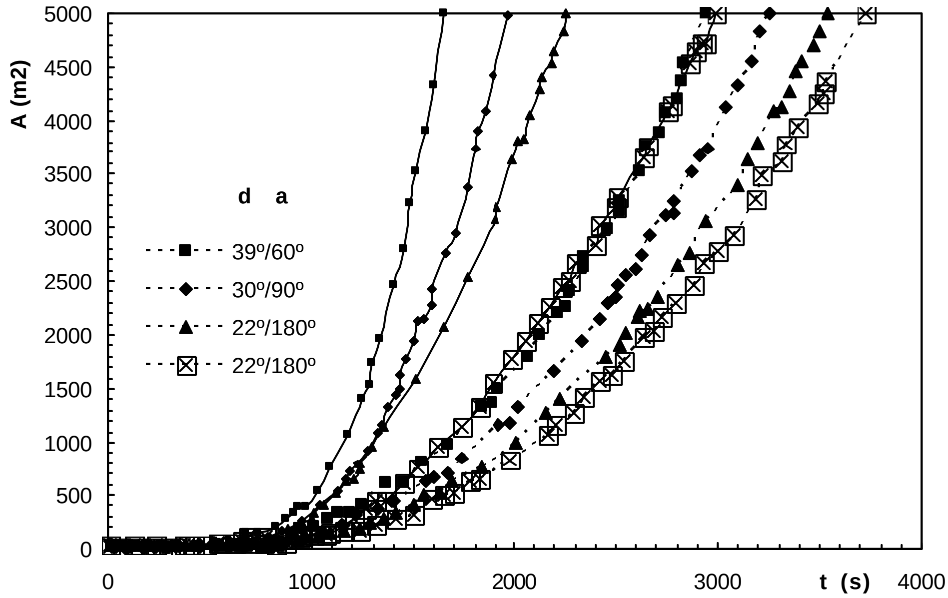


Figure 8 – Area growth in a canyon fire using static and dynamic simulations for four geometric configurations. The corresponding values of δ and α for each configuration are given in the legend. Dotted lines correspond to static model while full lines correspond to dynamic fire simulation.

3.4.3 Test of non-dimensional parameters

In order to test the formulation of non-dimensional parameters proposed above we used the results from Lopes (1994). The reference values that were adopted are shown in Table 3 for the two fuels used. As the simulation was made with a super-imposed wind flow it was considered that the reference rate of spread value should not be the basic rate of spread $\boldsymbol{R}_o$ (without slope and without wind). Instead we considered an alternative value (designated also as $\boldsymbol{R}_o$ here) for the same fuel bed on horizontal surface but with the same wind flow as considered in the simulation.

Table 3 – Reference values for fire simulation in a canyon (cf. Lopes, 1994)

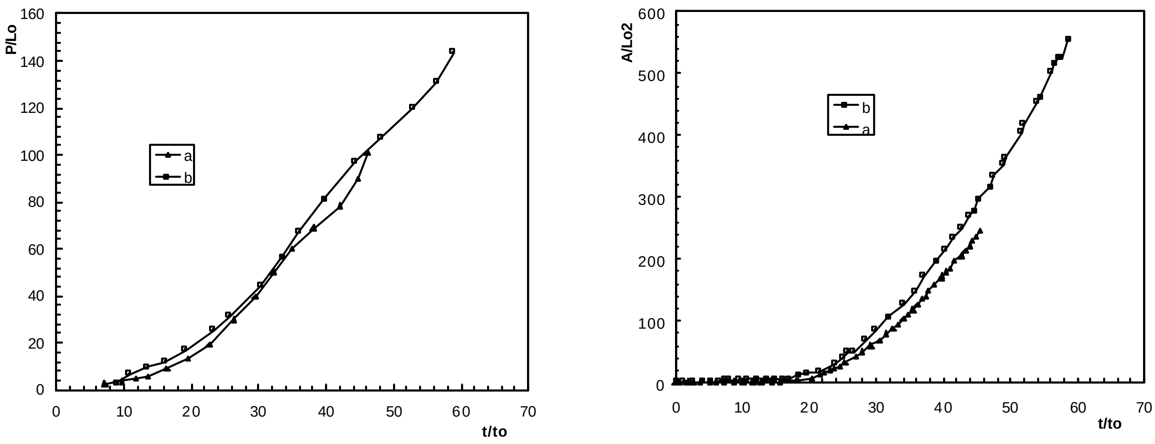
Fuel	R_o (cm/s)	U (m/s)	L_o (m)	t_o (s)
	0		5	

a	2	110	5	4.55
b	0.29	5.9	3	50.8

The results are shown in figures 9 and 10 for the simple plane and for a canyon with α=22º and δ=21º respectively. As can be seen the non-dimensional formulation works quite well, as both curves in the non-dimensional representation are practically coincident, for the simple plane slope and also at the initial stage of the canyon cases for both parameters.

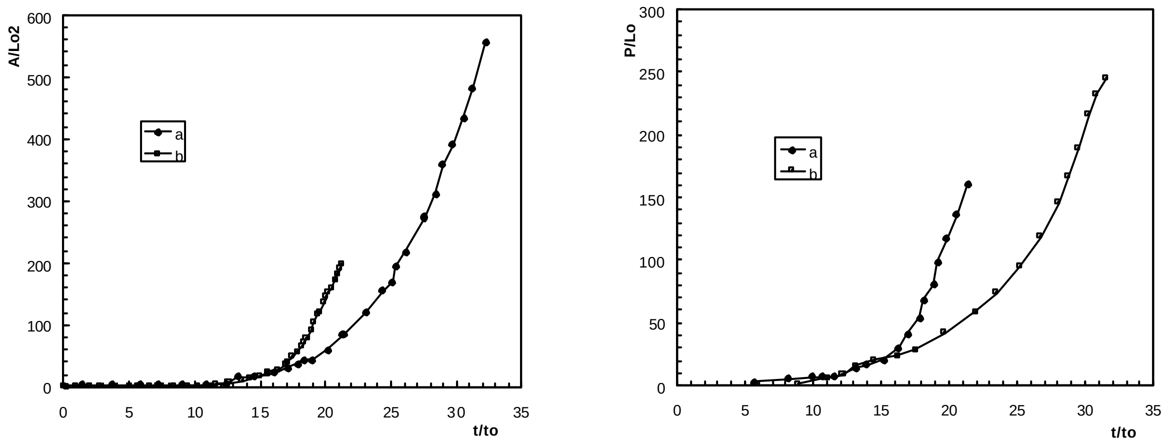
The configuration considered in figure 9 corresponds to a simple slope without "canyon effect". For this configuration the non-dimensional parameters work very well and the fire spread curves practically coalesce into a single one independently of the fuel bed.

The case considered in figure 10 is a canyon with a value δ=21º and it is observed that the non-dimensional parameters do not provide a single curve for both fuel cases as it would be expected. The fact that the non-dimensional curves do not coincide in the final stage of fire development indicates that most certainly a single set of reference values – namely $\boldsymbol{R_o}$ and $\boldsymbol{L_o}$ corresponding to the no-slope case – may not be sufficient to represent the fire conditions during all stages, namely during the "blow-up" that occurs at the final stage of a canyon fire as will be described below. The authors feel that the simplified non-dimensional modelling using only two parameters is not sufficient to describe fire spread in canyons when there is a blow-up. More research is required in order to clarify this point.



(a) (b)

Figure 9 – Non-dimensional evolution of perimeter (a) and area growth (b) for fuels ***a*** and ***b***, for a simple slope: α=22º and δ=0º.



(a) (b)

Figure 10 – Non-dimensional evolution of perimeter (a) and area growth (b) for fuels ***a*** and ***b***, for a canyon: α=22º and δ=21º.

4 Laboratory experiments

4.1 Test Rigs

In the experimental program three different test rigs were used.

The first one DE 1 (figure 11.a) was a preliminary rig adapted from the Combustion Table MC 3 of our Industrial Aerodynamics Laboratory. It had two faces inclined at a fixed value of δ=30º attached to a structure that could be inclined (0º<α<40º). A series of tests were performed on this table in order to assess the feasibility of analysing at a laboratory scale the main features of canyon fires. In spite of the small dimensions of the faces of this table (1.6x0.8m^2 each) the results were satisfactory so a larger device DE2 was built.

The structure DE 2 (figure 11.b) was built purposely for this research program and it is installed at the Forest Fire Research Laboratory of ADAI, in Lousã (Portugal). It has two faces (2.9x1.45m^2 each) that are hinged to a base allowing the setting of δ values for each face (0º<δ<40º) independently. The base is fixed to a structure and can be inclined manually (0º<α<40º). Practically all tests reported in this article were made in this test rig.

(a) (b) (c)

Figure 11 – Laboratory test rigs. (a) DE 1; (b) DE 2 and (c) DE 3.

The structure DE3 (figure 11.c) is basically the same as DE2 but its supporting structure was built on purpose allowing the setting of the desired values of α using hydraulic jacks to perform the movements.

A series of 20 experiments were carried out with different configurations in DE2 with the reference parameters given in Table 4. This set of experiments covers the large majority of the situations of canyons that are found in practice. Most results reported here refer to this set that is designated as basic set of experiments from now on. In Annex 1 a schematic representation of the 20 configurations studied in the basic set of experiments is given.

Table 4 – Geometrical properties of the Basic set of experiments in DE2

δ	α	θ	ϕ	ψ	Ref.
	0	11.0	0.0	90.0	*500*
	10	14.8	41.9	43.3	*501*
11	20	22.7	60.4	22.8	*502*
	30	31.8	68.8	14.2	*5003*
	40	41.2	73.2	9.7	*504*
	0	20.0	0.0	90.0	*505*
	10	22.3	25.5	59.3	*506*
20	20	28.0	43.2	37.7	*507*
	30	35.5	53.9	25.3	*508*
	40	44.0	60.5	17.9	*509*
	0	32.0	0.0	90.0	*510*
	10	33.1	14.0	69.9	*511*
32	20	37.2	28.7	51.9	*512*
	30	42.7	38.7	28.9	*513*
	40	49.5	45.8	29.5	*514*
	0	40.0	0.0	90.0	*515*
	10	41.0	11.7	73.8	*516*
40	20	44.0	22.2	59.1	*517*
	30	48.4	30.8	47.4	*518*
	40	54.1	37.5	38.0	*519*

4.2 Methodology

In the basic set of experiments the fuel bed was composed by dead needles of *Pinus pinaster* leaves with a load of 0.6 kg/m^2 (dry basis). In order to characterise the fuel bed in each session at least two tests of the basic rate of spread were made with a fuel bed created in the same conditions as in the main experiments. Fuel moisture content was monitored frequently during the experiments.

Tests were made also with other fuels, namely with straw. This fuel has the interest of having a much higher value of $\boldsymbol{R_o}$ for similar moisture content conditions (typically 0.6cm/s in comparison to 0.2 cm/s).

Fire ignition was produced at a single point in the OY_1 axis at a point placed 50cm above the base of the canyon (y_{ig}=50 cm).

During all experiments video and infra-red images of the evolution of the fire front were recorded.

Images were analysed using standard image processing systems. The algorithm for image correction due to non ortogonality of the optical axis of the cameras to the fuel bed surface developed by Andrá et al (2002) was used extensively. The analysis of fire spread was then carried out on these corrected images in order to retrieve various properties of the fire front advance at given time steps.

5 Results and discussion

5.1 Fire Shape

Shapes of the fire fronts computed using the analytical model for some of the canyon configurations studied are shown in figures 12, 13 and 14. In each figure combinations of the following values of the geometrical parameters are shown: α=0º, 20º and 40º; δ=11º, 20º and 40º. For each case the results from the experiments are shown for comparison for the same configurations and for the same time steps.

As can be seen the analytical model results are only a very crude approximation of the experiments. The bifurcation of the fire front with two distinct heads is observed only for low values of α and for high values of δ. Otherwise the fire front at the water line (axis $\mathbf{OY}_1$) tends to catch the other two heads merging in a single and wide fire front in most cases. It is also observed that the rate of spread of the head fire does not remain constant as it is assumed in the analytical model.

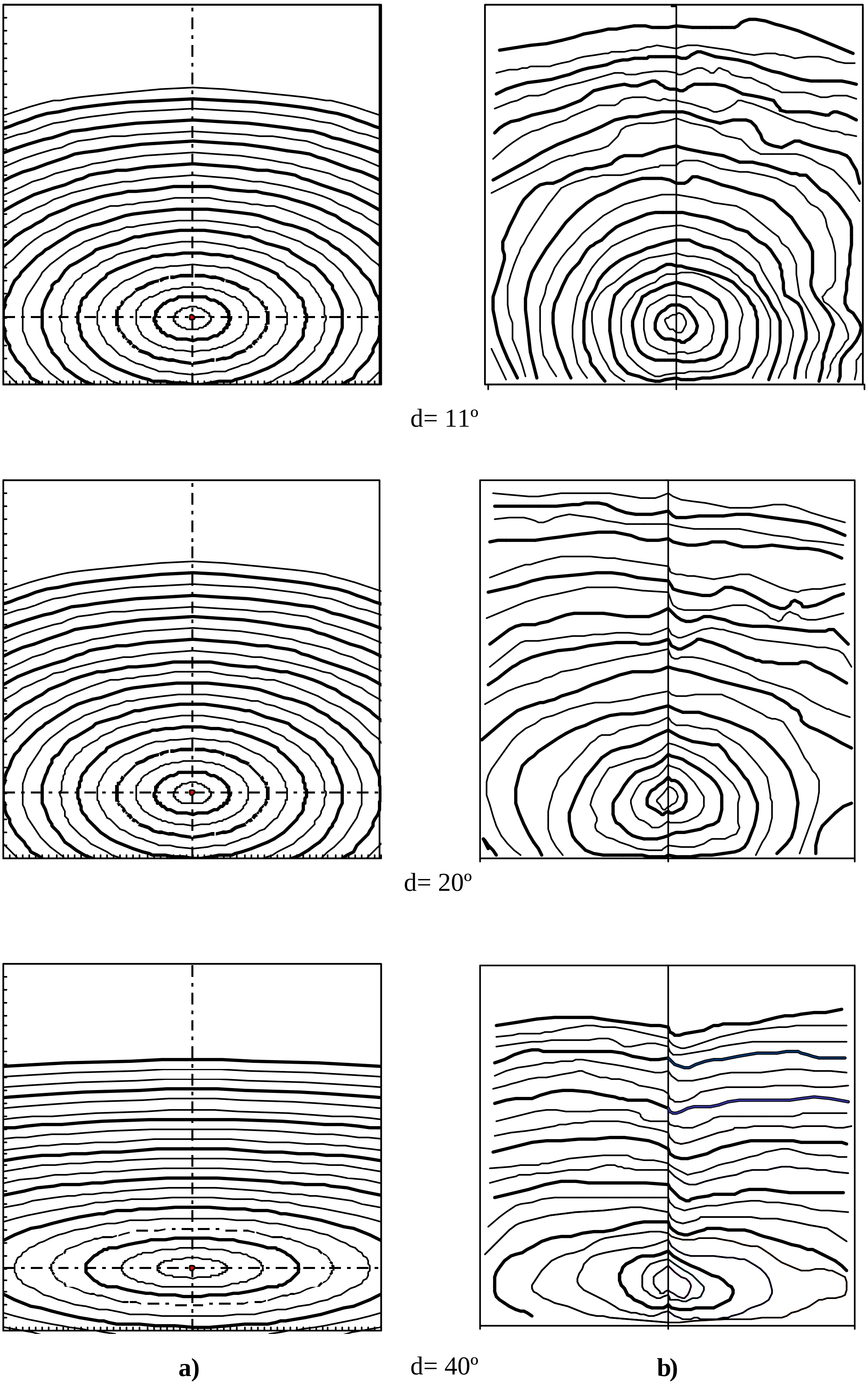


Figure 12 – Fire spread contours obtained in tests with α=0º for three values of δ. Time step between bold lines is 60 seconds. (a) Analytical model; (b) Experimental results.

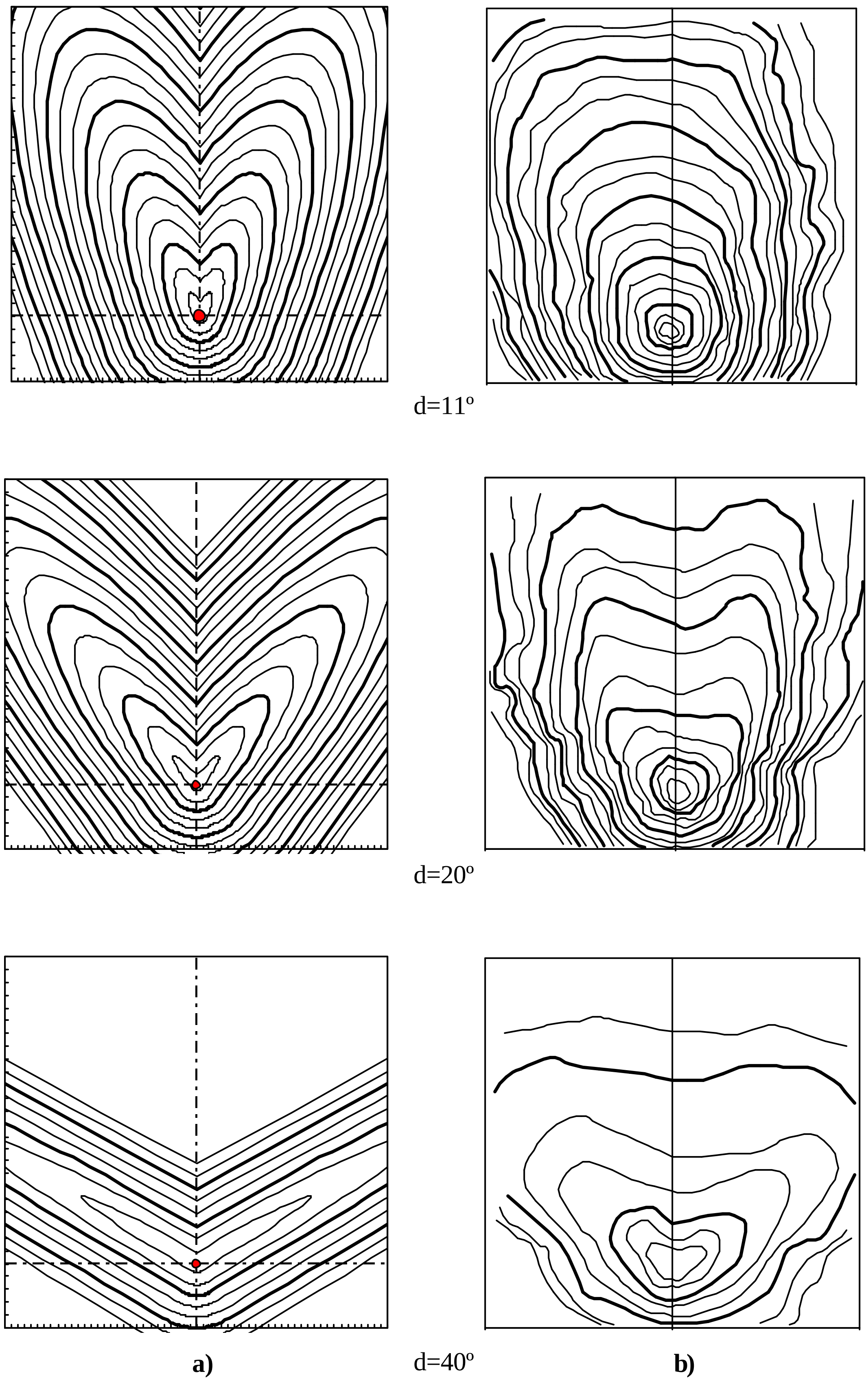


Figure 13 – Fire spread contours obtained in tests with α=20º for three values of δ. Time step between bold lines is 60 seconds. (a) Analytical model; (b) Experimental results.

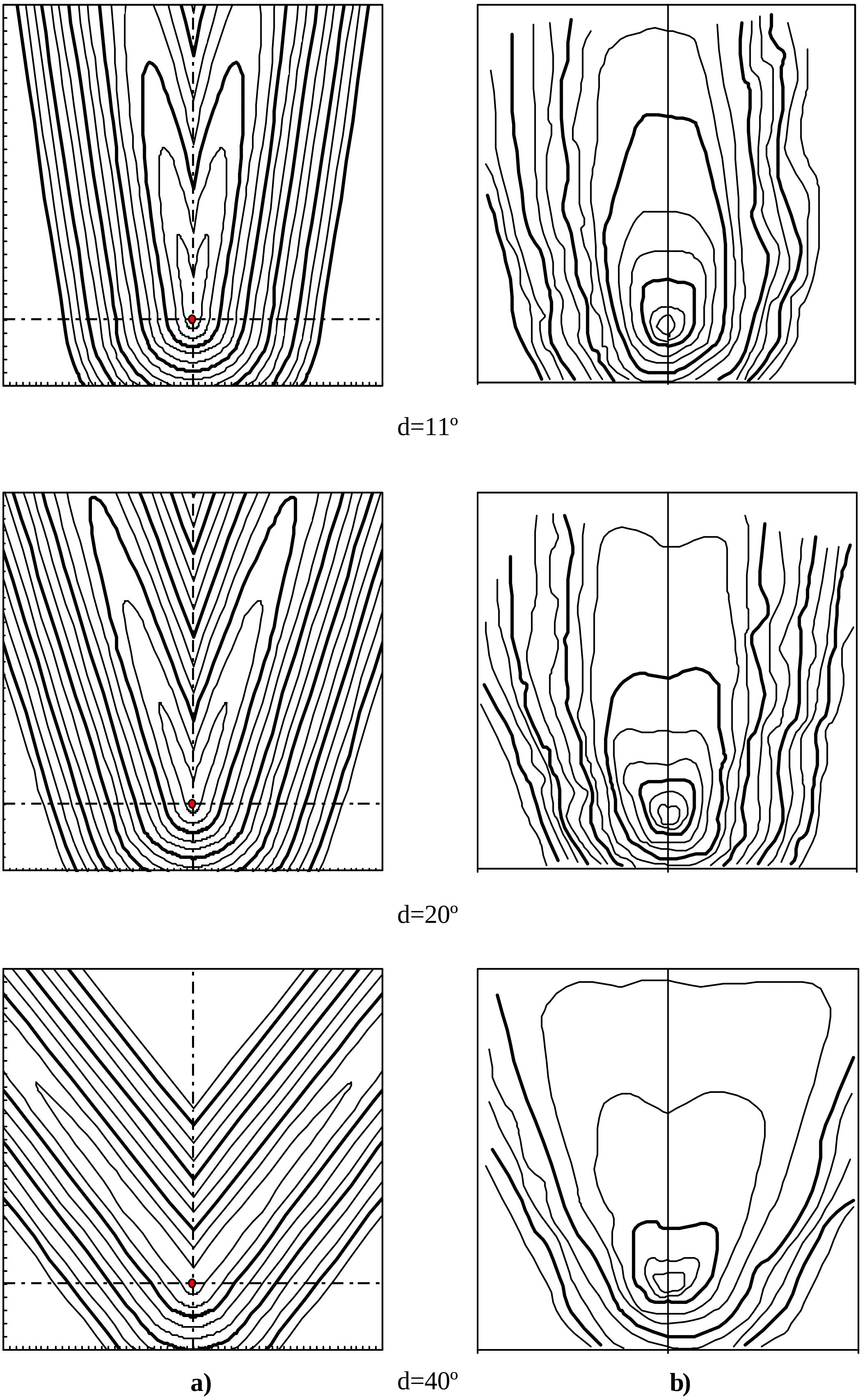


Figure 14– Fire spread contours obtained in tests with α=40º for three values of δ. Time step between bold lines is 60 seconds. (a) Analytical model; (b) Experimental results.

5.2 Rate of advance

5.2.1 Average values

In order to characterise the evolution of the fire front, namely to estimate a rate of spread at representative points of the fire front we considered the following four points P_1, P_2, P_3 and P_4, that were already considered above and are shown in figure 6. The distance s_i (i=1,4) was measured from the plots obtained in each test. It must be noticed that the evolution along direction s_4 does not correspond to a real rate of spread as this line is not perpendicular to the fire perimeter in the general case.

In a first step we estimate the average value of the rate of increase of s_i(t) assuming that this is a linear function of time of the type:

$$s_i = R_i . t + s_o \qquad [30]$$

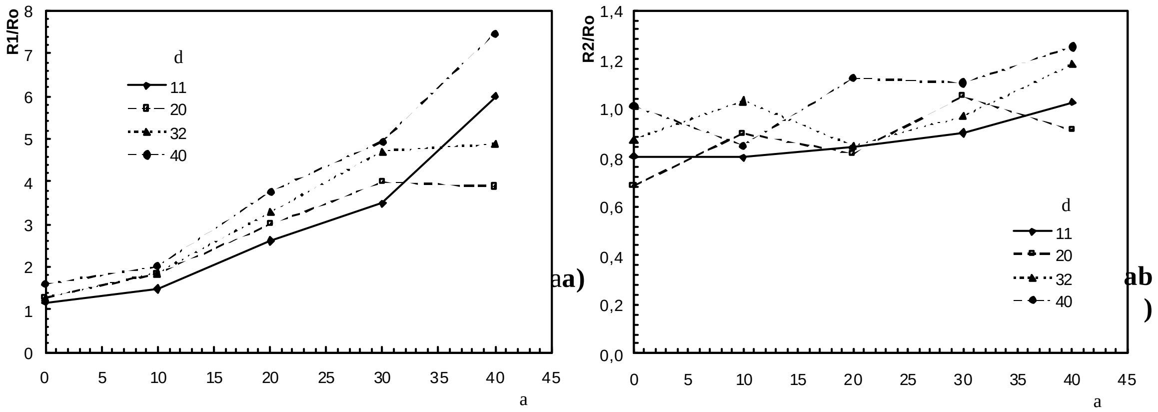
As will be seen later these average values of R_i are representative of the true rate of spread only in some cases of low values of α and/or δ. The results obtained for R_i are shown in figures 15 and 16. Given the dynamic character of canyon fire behaviour these average values of the rate of spread have a very weak value. They are given here as they were used to estimate the average rate of spread for the analytical model presented in section 5.1 above.

As can be seen in figure 15.a) the average rate $\mathbf{R}'_1$ of up slope spread along OY_1 axis increases with both α and δ. There is nevertheless a discrepancy for a=40º and for both d=20º and 32º that may be due to experimental errors. The average rate $\mathbf{R}'_2$ of down slope spread along OY_1 axis remains practically constant and close to one in the range of values of both α and δ that was tested, as can be seen in figure 15.b).

The average rate $\mathbf{R}'_3$ of up slope spread along the maximum slope axis that is shown in figure 16.a) increases with both α and δ. It must be remarked that the relative increase of the rate of spread with α is not so large as for the case of figure 15a). The average rate $\mathbf{R}'_4$ of horizontal spread at the level of the origin point remains practically constant with α for low values of δ and decreases for high values of δ due to geometrical conditions.

Comparison with the measured value of the angle of maximum spread (defined by the head fire) and the maximum slope angle ψ for each case is made in figure 17a). The full lines in this figure correspond to the geometrical model described in chapter 2 (equation [3]), these lines can be compared with those of figure 4. As can be seen the measured angle tends to be lower than the theoretical value. This means that the head of the fire is closer to the water line direction of the canyon indicating that there is a convective effect “pushing” the fire head towards the centreline of the canyon.

The average rate of spread $\boldsymbol{R}_3/\boldsymbol{R}_o$ as a function of slope angle θ is shown in figure 17 b). The dotted line that is shown in this figure is an extrapolation of the function given by equation [6] obtained for point ignitions in a slope without canyon effect (α=0º or δ=0º). As can be seen both sets of results of average values collapse quite well in a single curve.



(a) (b)

Figure 15 – Average value of the rate of spread R’1 along the water line for upslope propagation (a) and R’2 for down slope propagation (b).

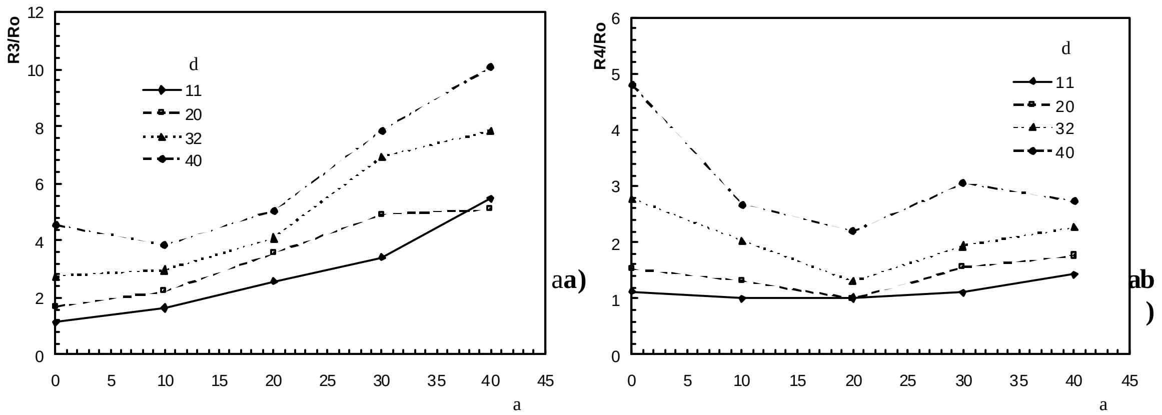
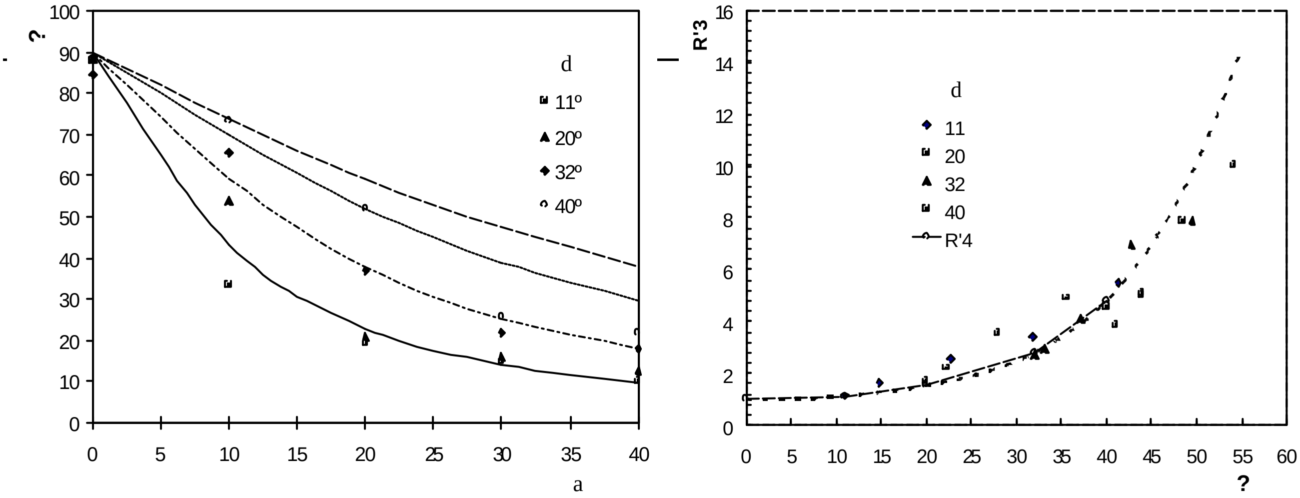


Figure 16 (b)

Figure 16 – Average value of the rate of spread R’3 along the maximum slope direction (a) and R’4 along a horizontal line at the level of fire origin (b).



(a) (b)

Figure 17 – (a) Direction of maximum spread compared with maximum slope direction ψ. The lines correspond to eq. [3]. (b) Non dimensional rate of spread R'$_3$ as a function of the slope angle θ. The dotted line corresponds to equation [6].

5.2.2 Dynamic analysis

As was said above the increase of the distance s_i from point P_i to the fire origin was not always a linear function of time. It was observed that on the contrary the rate of distance growth increased steadily with time in most cases. As an example the variation of s_1 as a function of time for the set of tests with δ=20º for each value of α is shown in figure 18. As can be seen in this figure the variation of s_1 with time can be considered approximately linear only for α =0º and for α = 10º. For greater values of α the increment of distance increases at each time step, corresponding to a non constant rate of spread. In these cases one observes that there is a relatively low value of the rate of spread at the beginning and then the rate of spread increases very rapidly. This is an effect of fire dynamics due to the feedback from the reactive fuel bed to the convection induced by the fire in the concave shape of the canyon.

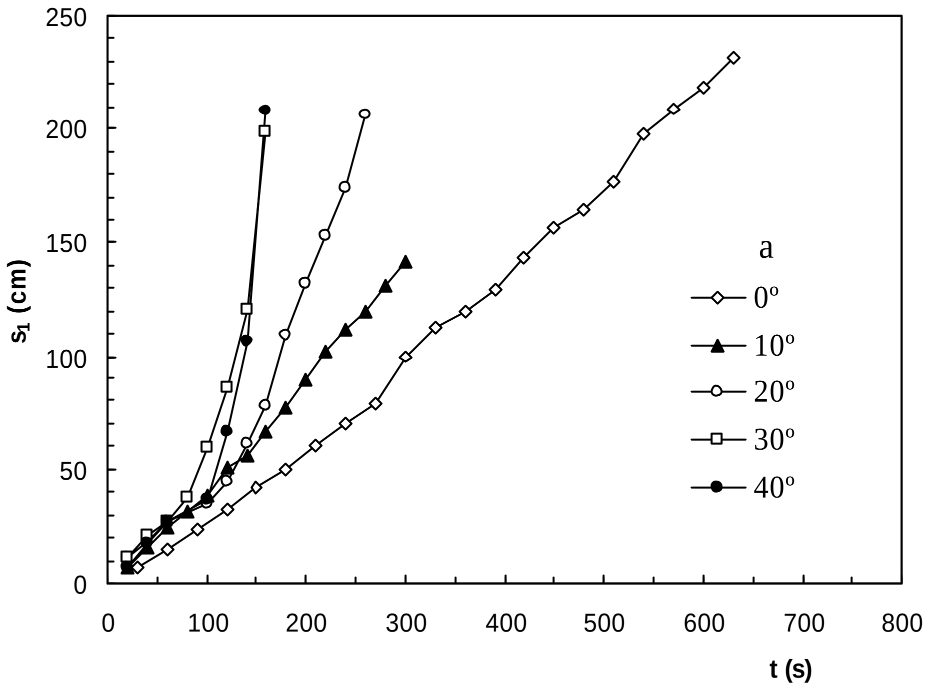


Figure 18 – Time evolution of distance s_1 of fire line to fire origin upslope along the water line for δ=20º.

The derivative ds_i/dt corresponding to an instantaneous value of the rate of spread in each case is presented in non-dimensional form:

$$f'_i = \frac{ds_i/dt}{R_o} \qquad [31]$$

The values of f'_1 for all the cases that were studied are shown in figure 19. In this figure it is clearly shown that the local rate of spread is not constant during fire growth in many cases and this feature is common to all values of δ. Our tests show that for α>30º the fire growth is dynamic in all cases and the rate of spread increases exponentially with time. For α=20º it has dynamic features for δ>20º. It is interesting to notice that the larger values of f'_1 are found for δ=32º while one would expect that they should be larger for δ=40º. This is probably due to the fact that the fire has not developed sufficiently in the limited space of the Combustion Table for this geometry.

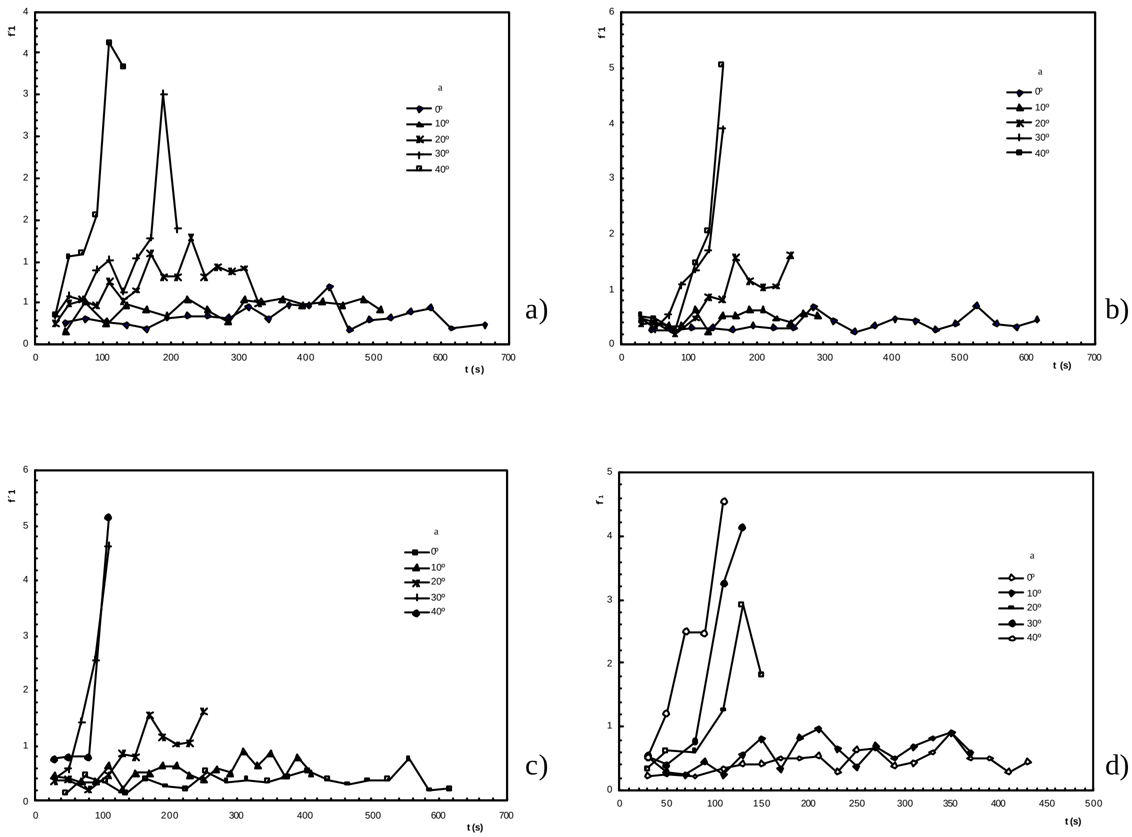


Figure 19 – Instantaneous non dimensional velocity ***f'₁*** of fire evolution along the water line for all cases that were studied.

5.3 Perimeter and area growth

Perimeter and area of the fire front during the period in which the fire front did not reach the border of the Table was analysed using the image analysis methods mentioned above.

As was shown above the fire growth in canyons has a dynamic character for the majority of cases. Therefore it is not relevant to analyse the average values of perimeter and area growth so only results for dynamic or time dependent growth are presented.

In figure 20 the temporal variation of fire perimeter in each case is shown. In this figure it is again clear that the rate of growth of the perimeter is not constant as predicted by classical fire behaviour models namely by the present analytical model. Interestingly it is found that in the range of our experiments the configuration δ=40º is the one that presents a linear growth of the perimeter for practically all values of α that were tested.

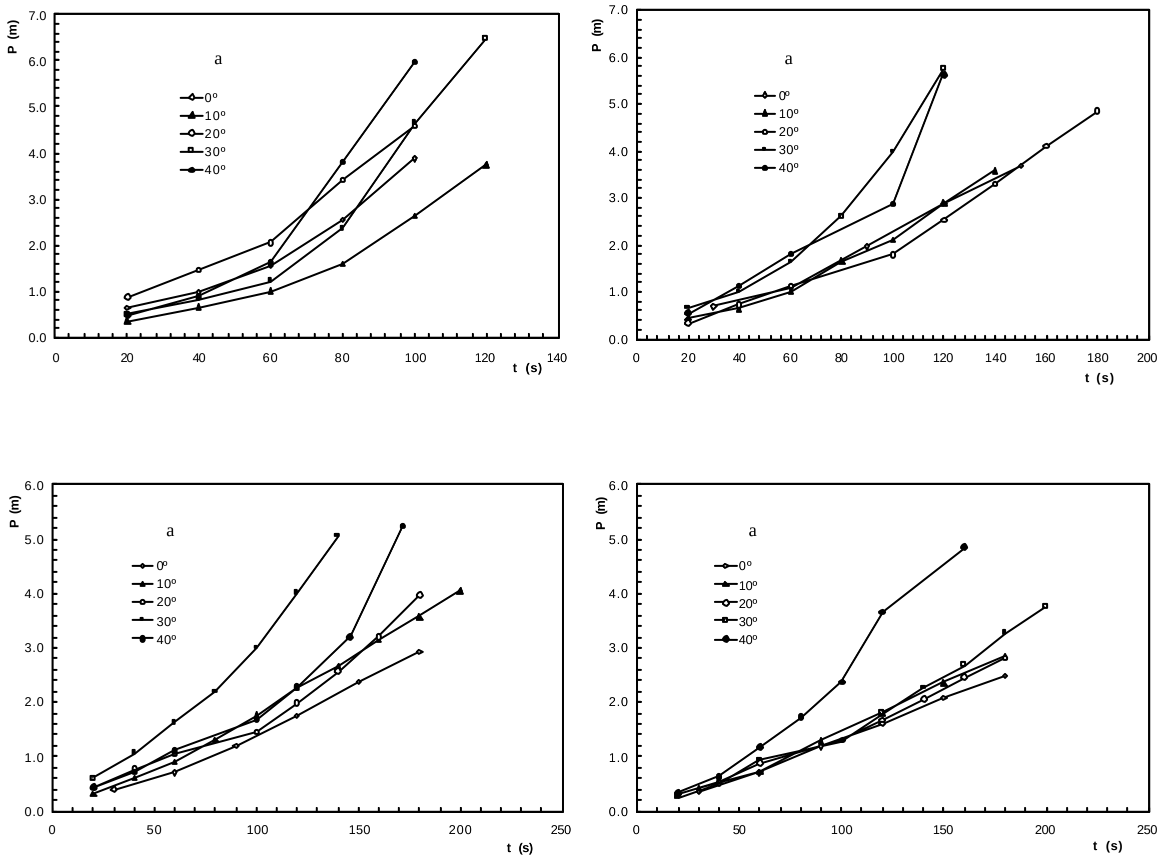


Figure 20 – Perimeter growth in each of the basic cases: δ=11º; 20º; 32º and 40º.

Area growth is shown in figure 21 for all the cases tested. The dynamic character of fire growth is also apparent in this figure.

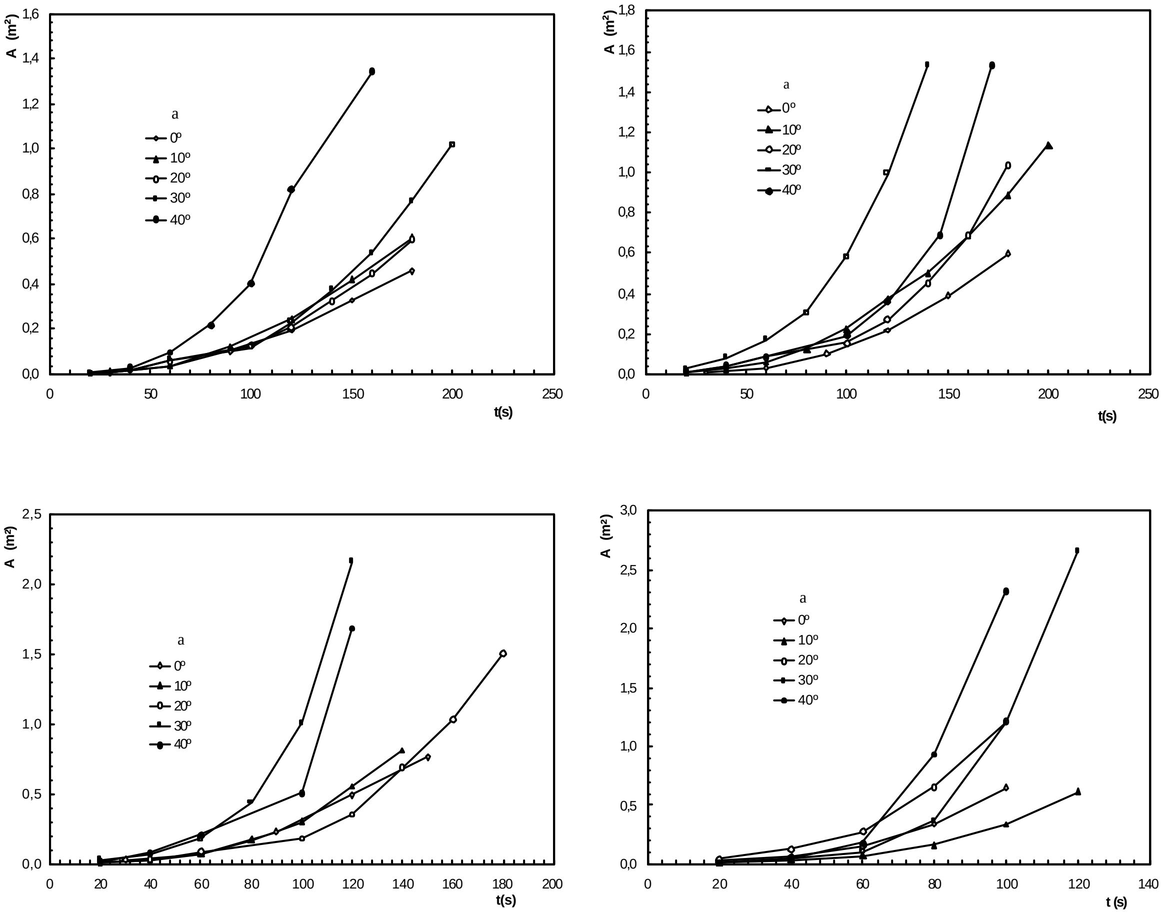


Figure 21 – Area growth in each of the basic cases: δ=11º; 20º; 32º and 40º.

5.4 *Test with two different fuels*

In order to test the proposed methodology using non-dimensional parameters to transpose results from one experiment to another situation two experiments were made with the same canyon geometry (δ=40º and α=40º) but with two different fuels.

In test DE521 the normal bed of pine needles was used while in test DE 522 a fuel bed composed of straw needles was used instead. A sequence of photos of both tests taken at practically the same time steps from ignition is shown in figure 22. As can be seen in this figure there is a marked difference between both fuels. The basic rate of spread, the flame length L_o were measured directly in both cases and the results are given in Table 5.

Table 5- Properties of the fuel beds with two different fuels tests

Ref.	Material	Load	FMC	R_o	L_o	T_o
		(kg/m^2)	%	cm/s	cm	(s)

DE 521	Pine needles	0.6	13	0.151	13.3	88.1
DE 522	Straw	0.6	9.7	0.577	21.7	37.9

The evolution of fire perimeter and fire area in both tests is shown in figure 23. Using the non-dimensional formulation proposed above the same properties are shown in non-dimensional form in figure 24. As can be seen in these figures the two sets of curves for P' and for A' are practically coincident at the first phase of the fire development (t'<0.7) but afterwards the agreement is not so good. This result is an indication that the basic fire spread properties – namely $\boldsymbol{R}_o$ and $\boldsymbol{L}_o$ – obtained for flat terrain conditions in the absence of wind are good similarity factors only for the initial stages of the fire. Once blow up starts fire is dominated by its own convection and its spread properties do not retain similarity to those basic parameters. Probably if we had used some other similarity parameters related to wind spread fire a better agreement would be obtained. The analysis of this assertion is left to future work.

The non-dimensional rate of perimeter and area growth, P" and A" respectively are shown in figure 25. The agreement between both sets of curves is not so good as before but it is considered to be sufficient to validate the proposed methodology of using the similarity laws defined by equations [22] to [25].

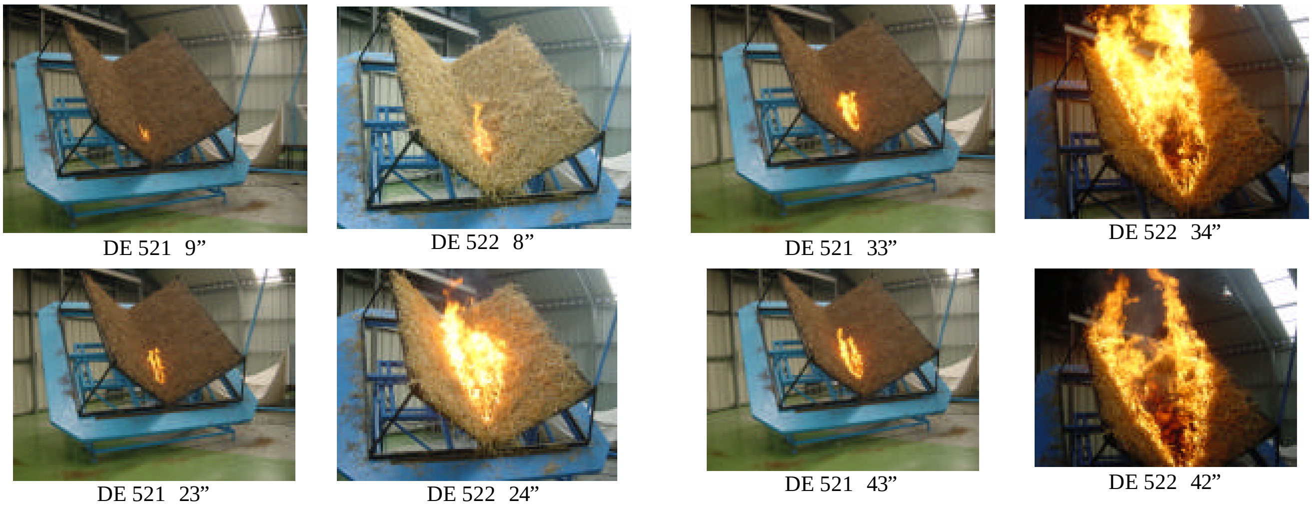
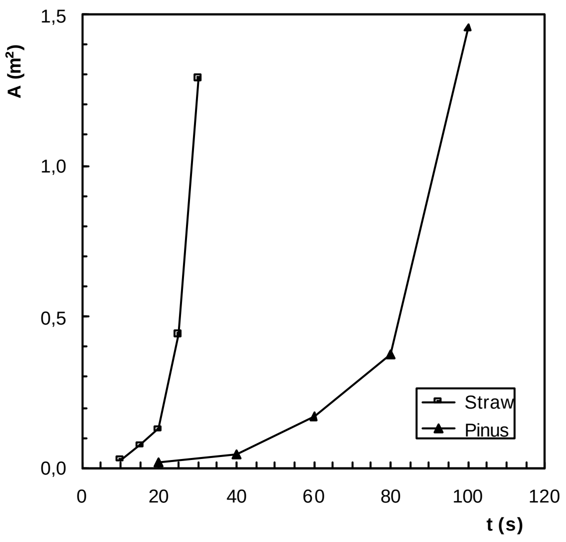
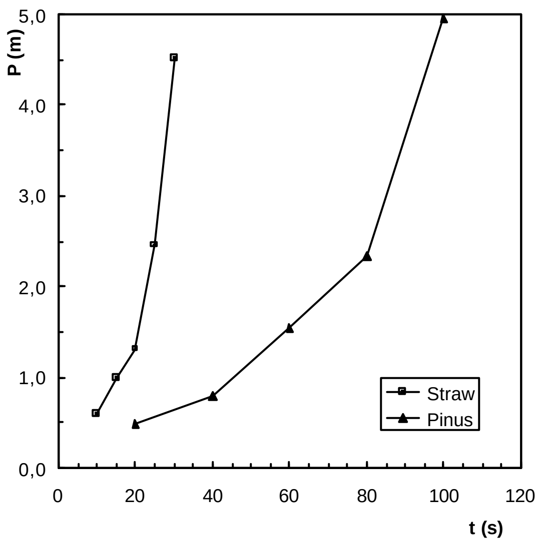


Figure 22 – Fire growth during tests DE 521 and DE522 with two different fuels. Time since fire origin in seconds is indicated below each picture.

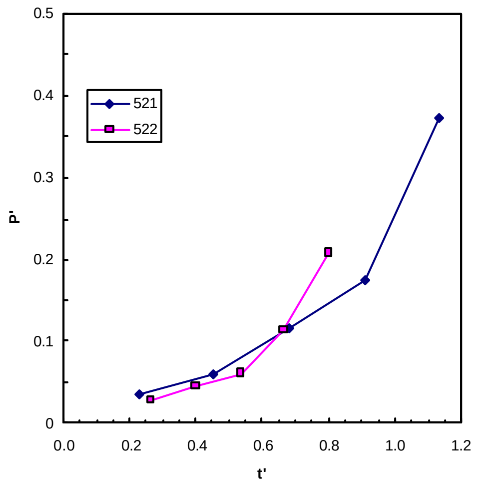


(a)

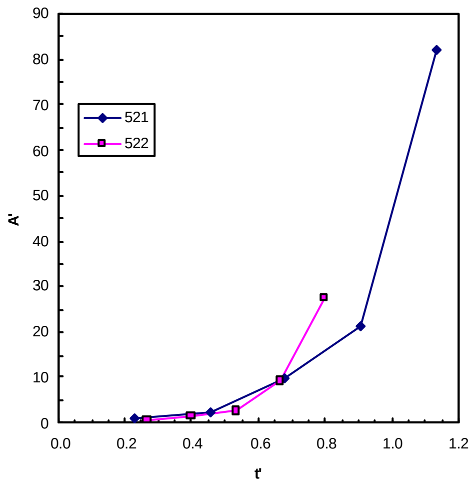


(b)

Figure 23 – Perimeter and area growth during tests DE 521 and DE522 with two different fuels.

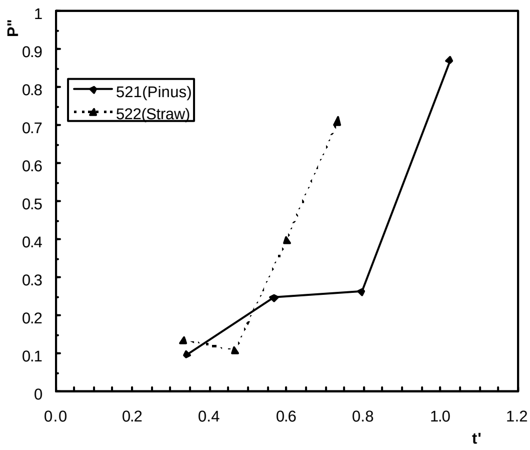


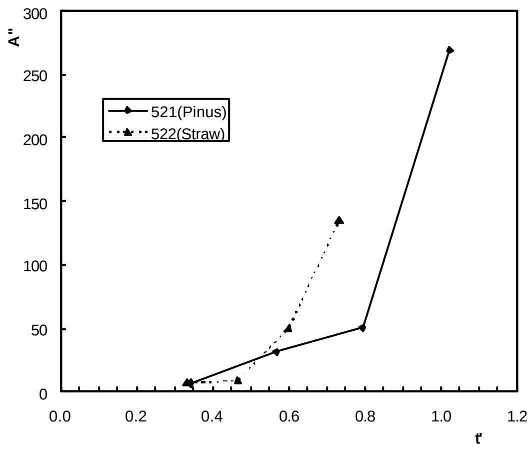
(a)



(b)

Figure 24 – Non-dimensional perimeter P' and area A' growth during tests DE 521 and DE522 with two different fuels.



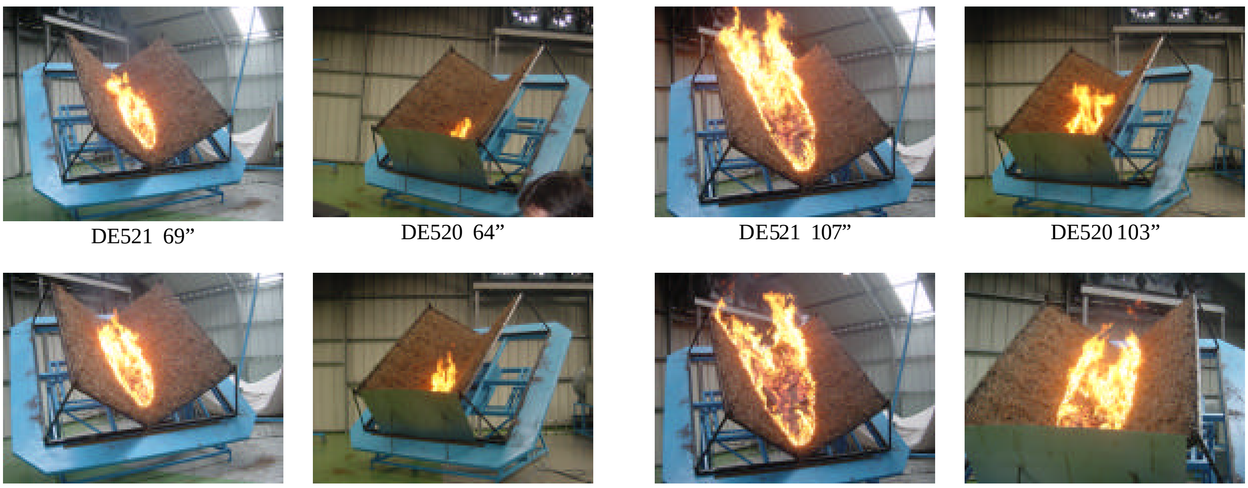


(a) (b)

Figure 25 – Non dimensional rate of perimeter P” and area A” growth during tests DE 521 and DE522 with two different fuels.

5.5 Convection inhibition

In order to put in evidence the role of convection induced by the fire in the dynamics of fire growth an experiment was carried out in which this convection was inhibited by a plate placed across the base of the canyon. A sequence of photos of tests DE 520 and DE 521 performed with the same fuel bed conditions and for δ=40º and α=40º with and without plate is shown in figure 26. The time steps of each pair of photos are not the same in all cases but they are sufficiently close to illustrate the large differences between both experiments.

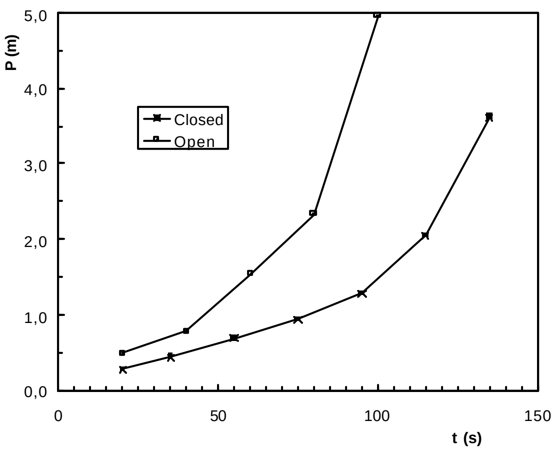


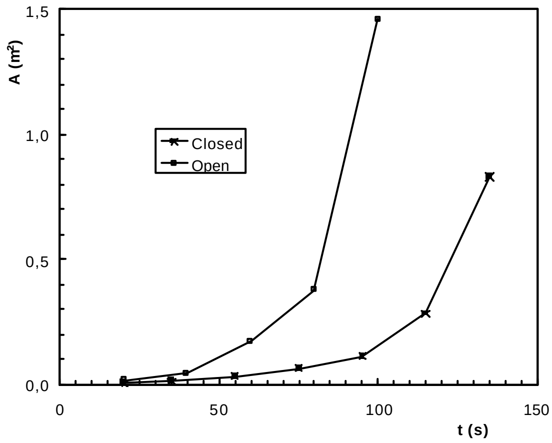
DE521 69” DE520 64” DE521 107” DE520 103”

DE521 78” DE520 84” DE521 124” DE520 124”

Figure 26– Fire growth during tests DE 521 and DE520 with open and closed canyon. Time since fire origin in seconds is indicated below each picture.

These results are put in evidence in the comparative analysis of perimeter and area growth for these two cases as it is shown in figure 27. The difference between both sets of data is quite clear showing the importance of air entrainment induced by natural convection.





(a) (b)

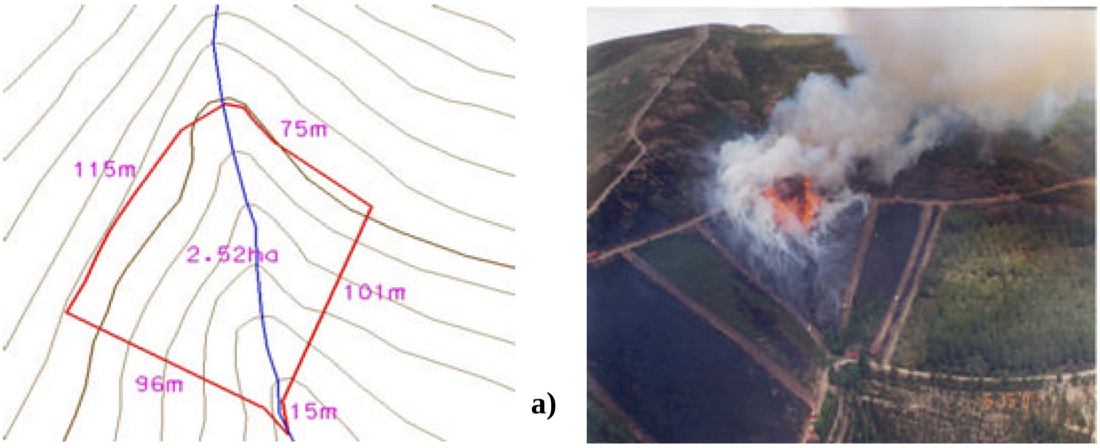
Figure 27 – Perimeter (a) and area growth (b) during tests with open and closed canyon.

6 Field cases

6.1 Field experiment

In the scope of Gestosa field experiments in Central Portugal (cf. Viegas et al. 2002) a test of fire propagation in a canyon was performed in June 2001 in a plot designated G 63. Vegetation cover of this plot was shrubland with an average height of 0.87 m and a fuel load of 3.7 kg/m^2. The general dimensions of the canyon and a general view of the experiment are shown in figure 28. The canyon configuration corresponded approximately to the following values α=25º and δ=31º.

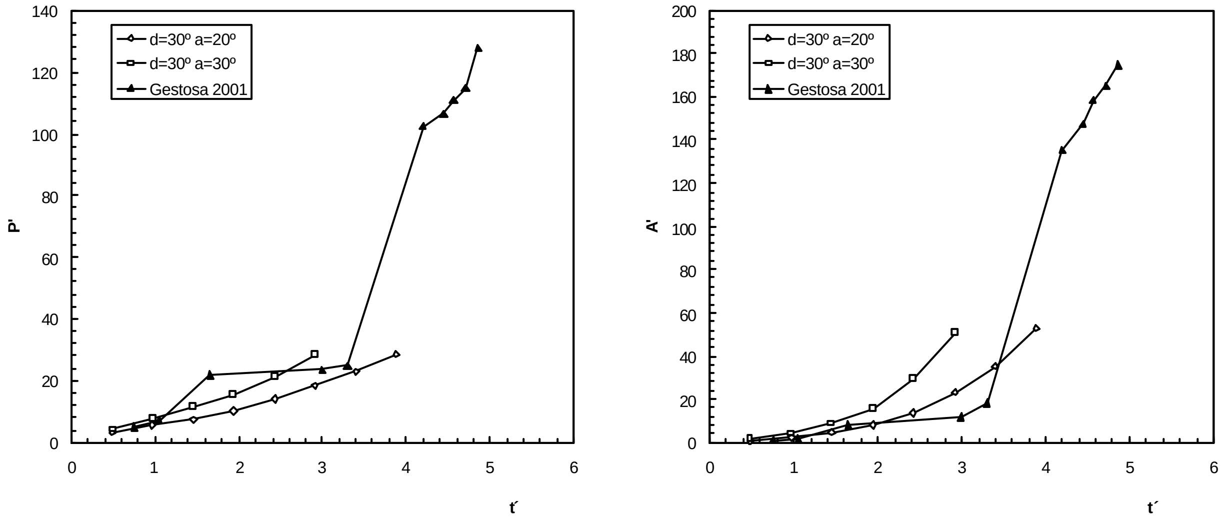
Extreme precaution was taken during this test to avoid fire escaping to surrounding vegetation. Ignition was performed at two points near the water line at the base of the canyon. The total duration of the experiment was 32 minutes. Characteristically more than 30% of the area was burned during the last four minutes of the experiment.



a) b)

Figure 28 – Canyon field experiment G 63of Gestosa 2001. (a) Contour map. (b) View of the test site during the final stages of the experiment.

Using the following reference values for the field case the perimeter and area growth in non-dimensional form were plotted: $\boldsymbol{R_o}$=0.06m/s; to=400s; ($\boldsymbol{L_o}$=12m) in figure 25. In the same figure the corresponding results for laboratory tests for δ=30º and α=20º and α=25º are shown for comparison. Assuming that the reference values are taken correctly it appears that the laboratory tests show the same trend as those observed in the field although the range of variation of the parameters, namely non-dimensional time, was not sufficient in the small scale experiments to allow a definitive conclusion.



(a) (b)

Figure 29 – Non dimensional perimeter (a) and area growth (b) in the field experiment compared with laboratory tests for two different configurations.

6.2 Real fires

There are many examples in the literature of fire related fatalities that occurred in canyon or similarly shaped terrain. To refer just a few that are well known in the literature we mention Mann Gulch Fire (cf. Rothermel, 1993, Mac Lean, 1992), Storm King Fire (cf. Butler at al., 1998), Thirtymile Fire (cf. Furnish et al., 2001), Loop Fire, 1966, and the Battlement Creek Fire, 1976, (cf. Pyne, 1984), Alajar Fire (cf. Silva, 1997), Alvão Fire (cf. Viegas et al., 2001). In the description of these accidents it is frequently mentioned that a "blow-up" of the fire or a "sudden explosion" occurred. It is always mentioned that the fire behaviour changed suddenly and in an unexpected way so as to surprise all involved. It is also reported that the fire consumed in very few minutes an area larger than that burned during the previous hours or even days in the same area and type of fuel. Witnesses and survivors report strong to very strong winds in the area of the fire, even when the overall winds in the region were weak. The report on Storm King Mountain accident in particular is very detailed and informative in this aspect.

In order to explain the sudden change of fire behaviour some analysts assume the existence of special phenomena that contribute to the observed and apparently unexplained fire behaviour. For example Butler et al. (1998) mention a 'Venturi effect' of the wind around the Storm King Mountain to justify the sudden acceleration of the fire. These authors also hypothesize about the interaction between general wind and up-canyon flow to justify the extreme fire behaviour observed. They also look at the possible occurrence of severe spotting ahead of the fire line as a mechanism to induce fire acceleration. Silva considers that a thermal belt at mid slope provoked fire acceleration in Alajar Fire. The report on the Thirtymile accident makes only a very short reference to topography in its analysis of factors contributing to the rapid fire spread during the final stages of the fire although in our opinion this was certainly one of the major factors in the very rapid fire development.

Our experiments show that these special effects are not at all necessary to produce a blow up in a canyon. The terrain itself and the concave shape of the canyon are enough to generate the dynamic behaviour of the fire as was observed even at the relatively small scale of our laboratory experiments. There was no wind at all inside the laboratory and even less stratification effects or fuel bed heterogeneities that could provoke the observed behaviour.

Therefore in our opinion some of the analysis that was produced in past accidents involving canyons can be misleading and even dangerous. As some of them invoke the conjugation of a set of special circumstances that one might expect to be rare or with a very low probability people may be induced to take a chance and put their lives in danger in a canyon fire. Our results show that a blow-up will always occur in a canyon even if it is quite shallow. It is not necessary to have any wind flow blowing over the fire and even less any sudden burst of wind. The only things that are needed are space and time for the fire to accelerate and to create its own wind. If these conditions are available no one should ever be placed in the way of such a powerful fire front.

7 Conclusion

This study is a first approach to the analysis of fire spread in canyons based on analytical and on experimental work. The simple case of symmetrical canyons with plane faces, uniform vegetation and single and symmetrical point ignition without wind was considered. It was shown that two angles are sufficient to characterise the geometry of the canyon in this case.

An analytical model to estimate fire growth based on the concepts of semi-elliptical growth and assuming a constant rate of spread for the head fire showed that fire shape depends only on the maximum slope angle θ of the canyon face and on the angle ψ between the maximum slope direction and the water line of the canyon. This model is very limited as the assumption of a constant rate of spread is not valid and also because it is observed that in some cases the strong convection induced by the fire masks the bifurcation effect predicted by the model in all cases.

Non-dimensional parameters are proposed to compare data from numerical or physical experiments performed at different scales or with different fuels. The present results can be considered a preliminary and limited validation of the proposed method of transferring and comparing data.

The results of the numerical model developed by Lopes et al. (1995), for the simulation of the behaviour of fire in a canyon were recalled. The predicted but not yet validated dynamic behaviour of fire in this terrain configuration was demonstrated in the present study.

A laboratory experimental program carried out in an original test bench was described. A wide range of geometrical configurations was covered in the present study. All tests were recorded using video and infra-red cameras. An original algorithm was used to correct the images due to oblique incidence of the cameras and fire spread analysis was performed using a very large number of images collected during the experiments.

The dynamic behaviour of the fire was clearly observed in the sense that for the majority of cases the spread of the fire is governed by a time dependant rate of spread. This effect is not predicted in classical models. These models assume that a fire in a homogeneous fuel bed in a uniform slope will propagate with a constant rate of spread. This is not at all the case.

It was observed that the fire growth is relatively slow at the beginning but suddenly the rate of fire growth increases very rapidly. The time lag for transition must depend on geometry and on fuel properties. Our results show this dependence but are not sufficient to allow for more definitive or quantitative conclusions at this stage.

The fire behaviour mentioned above can be misleading in fire suppression activities. The fire appears to be well behaved when it is at its initial stages near the bottom of the canyon. When sufficient convection is generated by the fire it feeds the combustion reaction with fresh oxygen then the process enters in an unstable equilibrium with the rate of spread increasing probably exponentially and reaching values that are not commonly observed for the same type of vegetation. Our study showed that there are no additional conditions like fuel changes, strong winds or stratification effects required to provoke fire acceleration in this terrain configuration.

A laboratory experiment performed with a plate to inhibit air entrainment at the base of the canyon demonstrated the very important role played by natural convection in this type of fires. A well monitored field experiment in a canyon showed the same fire behaviour as was observed in the small-scale experiment. The non-dimensional parameters that were used showed a similar trend for both sets of data.

Past cases of fires in canyons can be explained at the light of present study. In particular the phenomena described in accidents involving fatalities that occurred in canyons can be explained based only on terrain features. Although the existence of some other special circumstances in some of them cannot be ruled out it was demonstrated that such conditions are not at all necessary for a blow-up to occur. This conclusion has very important practical implications in terms of fire safety as it implies that fires in canyons are always potentially very dangerous. Exposure to fire spread above the fire line should be eliminated by all means in order to avoid loss of lives. If there is no absolute certainty that a fire at the bottom of a canyon – or a very steep slope – can be extinguished in a very short time with the existence fire fighting force one should never attempt to encircle the fire or to put resources at any place in the slope above the fire as the high rate of spread regime can be attained suddenly. According to our study this is only a matter of time for a given terrain configuration and it does not depend very much on other ambient conditions.

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Annex 1

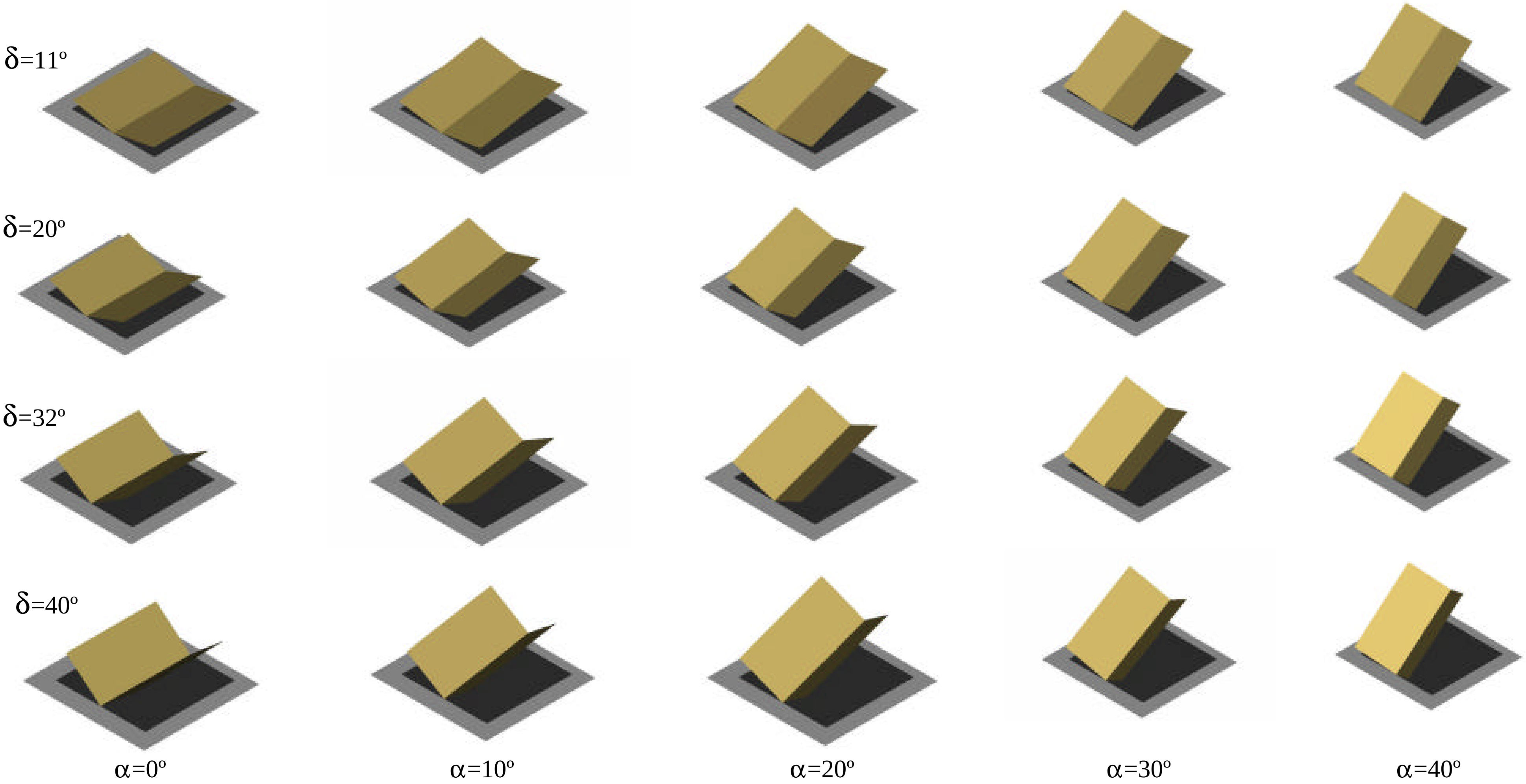

Figure A 1 – Schematic view of the various configurations studied in the basic experimental program.