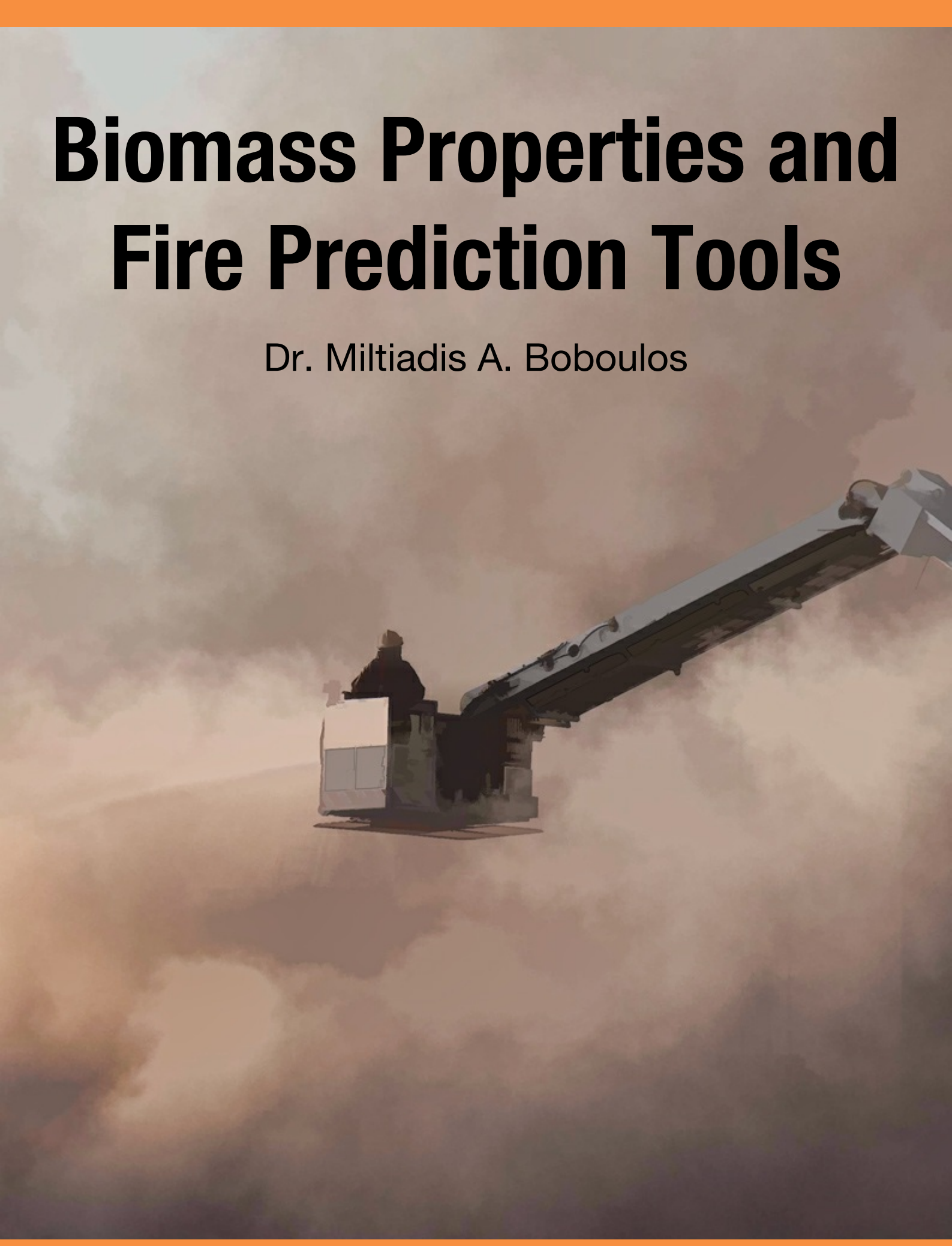
Biomass Properties and Fire Prediction Tools

Dr. Miltiadis A. Boboulos



bookboon
The eBook company

Dr. Miltiadis Boboulos

Biomass Properties and Fire Prediction Tools

Biomass Properties and Fire Prediction Tools
1st edition

ISBN 978-87-7681-627-8

Contents

1 Biomass Properties and Prediction Tools for Vegetation Wildland-Urban Interface (WUI) Fires

1.1 Overview

Wildland fires are natural calamities that bring enormous environmental and economic damage worldwide and some of them cause human death. Achieving effective fire fighting is associated with the possibilities of predicting the characteristics of fire behaviour. Special attention needs to be drawn to meteorological conditions and their effect on fire spread in a bed of vegetation. On the other hand, studying the effect of forest fires on the environment is of equal significance for building the strategy and specific actions to be undertaken in the fire fighting process. Especially, Mediterranean climate countries are subjected to higher risks of fires and all the damage they involve.

This material presents a review on related literature involving main characteristics and fire behaviour prediction models for surface fire and especially for pine litter species. The first part of this section presents experimental data for various characteristics of pine needle species, and also results from laboratory observations and studies for fire behaviour in a vegetation layer comprising above species. The second part gives consideration to various types of models used to predict the behaviour of surface fires. Also presented are basic approaches employed in describing the processes involved in the heating up, ignition and burning of the vegetation, and also the effect of these processes on the parameters of the flow in the fire zone. Data for model verification are also presented.

1.2 Research in the Field of Occurrence and Spreading of Forest Fires

Three components should be simultaneously available in order for a forest fire to occur: *fuel (forest vegetation*), oxygen and a heat source.

Fuels in the forest can be divided into four heights (Missbach et.al., 1982):

- Vegetation of a height of above 2 meters,
- Shrubs and low-height trees up to 2 meters high that are most commonly encountered in the Mediterranean region. Major representatives of these species are various shrubs and grasslands;
- A layer of dry grass and tree leaves litter;
- Soil cover bed.

Fires occurring in the last three groups are considered surface fires.

Experiments carried out to examine the vegetation's susceptibility to ignition and the behaviour of the different types of vegetation as a fuel bed resulted in final output and obtained values for the so called fuel particle characteristics. The latter are among the basic data used to design the fuel models.

On the other hand, the studies and the assessment of the intensity and the risk of occurrence of forest fires are based on the determination of fire behaviour characteristics. The most common task involved in obtaining the rate of spread of the fire under various surrounding conditions and for different types of vegetation species is to establish the current location of the fire outlines along a given direction and also the average rate of variation of these outlines – the rate of fire spread (ROS).

In order to combat successfully the ignition of forest vegetation and to fight the fires that occur, one of the conditions is the availability of adequate tools to predict the behaviour of forest fires. Various models are being developed and used to act as tools to determine individual fire behaviour characteristics or parameters in the fire zone. These models are obtained using various approaches and these vary from statistical processing of experimental data to the presentation of a detailed physical and mathematical picture of processes associated with the occurrence and spreading of the fire.

1.2.1 Strengths and Weaknesses of Literature

Generally, a literature survey of the problematic of a study allows to acquire information which can then be used as a basis for analysis of problems and to outline the areas where the main efforts and resources should be concentrated.

A large amount of information is available in the readily accessible literature sources for fuel particle characteristics (mainly physical ones) for different vegetation species of low and medium height, characteristic of the Mediterranean European regions. This also provides a possibility to determine these characteristics by means of studies using samples in laboratory conditions and employing simple methods and settings.

Another strength of the literature sources is the collected information and the studies carried out with the aim of developing models to be used for predicting the outlines of the fire and the fire rate of spread based on statistical processing of data on these characteristics. The most intensive studies in this area and, respectively, the most comprehensive data is to be found for fires in vegetation beds comprising shrubs from the region of Australia, as well as some studies for North America – the US and Canada.

The possibility for using a data base which compiles numerous reports from studies that have been carried out is also one strength of the literature survey. The EUFIRELAB data base provides comprehensive information on activities involved in the prevention of forest fires in the Mediterranean countries. This data is structured observing the relevant characteristic attribute feature and provides possibility to trace the developments in the study and the achievements in the relevant areas. Another advantage is the possibility to establish direct contact with the authors. Another powerful data source is the International Journal of Wildland Fire and this is the formal scientific edition of the International Association of Wildland Fire.

Weaknesses involved in the available literature sources for experimental studies lie in several basic aspects. Data on fuel particle characteristics for each individual type of vegetation species vary (in terms of number) within wide ranges. This is true for both data provided for the same region, and also for comparison studies for several different regions. These differences are due to the variations in the characteristics of vegetation particles resulting from the different climatic conditions, as well as to the different methods and methodologies adopted for determining those characteristics. Data on the methods employed is just as scarce and hinders the assessment on the applicability of these literature data.

Determining fire behaviour characteristics under laboratory conditions is suitable for small scale fires which comprise the group of fires occurring in low height (depth) vegetation beds. Therefore, laboratory experiments are only limited to studying mainly fires occurring in pine litter other then forest litters. A limitation in these experiments is also the space (time) for modelling the phenomena and hence, for obtaining data for large scale fires and well established fire behaviour characteristics. The experiments for modelling surface fires into “live” vegetation layers (shrubs, grasslands) need to be performed in actual conditions and this makes it difficult to organize them and to provide the necessary measurement equipment, as well as making them more expensive. Therefore, literature sources providing evidence for such type of experiments are very rare.

Data on thermal decomposition and combustion of different vegetation species is also very scarce in the literature sources considered herein under. Experimental studies in this area are hindered by the need for using complicated and expensive laboratory equipment and installations, as well as by the complex nature of the processes involved in the modelling of close to actual conditions. The theoretical modelling of such processes is rather complicated and they need to be simplified in order to obtain results that are applicable for the relevant field.

Studies in the field of fire behaviour for vegetation occurring in the region of Greece are very limited and much less for other Mediterranean European countries, such as Italy, France, Spain and Portugal.

According to Allgower et al. (2002) some of the gaps in modelling the fire behaviour are linked to the fact that ignition and maintenance of the fire are a function of various conditions determined in turn by an overall fuel complex. However, in experimental studies the attention is concentrated basically on the formation of fuel models to be used to describe the relevant type of vegetation species. However, the latter are only part of the overall fuel complex. Another drawback of the modelling of forest fires is the fact that propagation modelling is not yet really ready for 3D-fire spread modelling over vast areas. This is preconditioned both by insufficient theoretical studies in this field, and also by the high computational cost pf the numerical experiments and this becomes an obstacle for shifting from small-scale combustion modelling to larger-scale 3D-fire propagation modelling. Another gap encountered in fuel description and modelling is how surface fires spread into active crown fires.

1.2.2 European Programs

A major role in the development of research programmes in the area of forest fires for the region of the Mediterranean countries is played by the organization EUFIRELAB (www.eufirelab.com). The EUFIRELAB is a Euro-Mediterranean wildland fire laboratory, a wall-less laboratory for wildland fire sciences and technologies in the Euro-Mediterranean region.

EUFIRELAB is structured in units aimed at reinforcing the co-operation among Euro-Mediterranean teams, activating large exchanges of knowledge and know-how, developing common concepts, approaches, and "languages" and fostering the common use of facilities for research and/or technological development. The major fields of research on the issues of forest fires (as indicated with codes), distributed among individual research teams are:

1. WP02 Wildland fuel description and modelling unit
   - WP02T1: State of the art and survey
   - WP02T2: To elaborate common methodologies

2. WP03 Wildland fire behaviour modelling unit
   - WP03T1: State of the art and survey
   - WP03T2: To compare the different types of models
   - WP03T3: To define common procedures for
   - WP03T4: Towards a European scale of magnitude of wildland fires for characterising the intensity of wildland fires and prescribed burnings

3. WP04 Wildland fire, ecosystems functioning, and bio-diversity unit
   - WP04T1: State of the art and survey
   - WP04T2: Fire impacts on the different components of the ecosystems
   - WP04T3: Methodologies and tools for analysing and monitoring vegetation dynamics and restoring burned areas
   - WP04T4: Prescribed burning, a tool for managing bio-diversity and ecosystems functioning

4. WP05 Socio-economy unit
   - WP05T1: State of the art and survey
   - WP05T2: Towards common methodologies for investigating on wildland fires causes and factors
   - WP05T3: Towards common methodologies for studying the costs-to-benefits ratio of wildland fires prevention

5. WP06 Decision support tools unit
   - WP06T1: State of the art and survey
   - WP06T2: To elaborate common specifications for further decision support systems

6. WP07 Widland fire metrology unit
   - WP07T1: State of the art and survey
   - WP07T2: Towards common methodologies for collecting data during laboratory experimental fires
   - WP07T3: Towards common methodologies for collecting data during outside fires
   - WP07T4: Centre for technological development

7. WP08 Widland fire risks and hazards unit
   - WP08T1: State of the art and survey
   - WP08T2: Common methods for mapping wildland fire risks
   - WP08T3: Towards a Euro-Mediterranean Wildland Fire Danger Rating System

8. WP09 Wildland fire suppression unit
   - WP09T1: State of the art and survey
   - WP09T2: Towards common methodologies for wildland fire suppression planning
   - WP09T3: To improve the safety and efficiency of the fire fighters

9. WP10 Widland – urban interfaces management unit
   - WP10T1: State of the art and survey
   - WP10T2: Towards common methodologies for managing wildland-urban interfaces

Morvan (2004) present the basic characteristics of the initial versions of ten codes of behaviour models, developed in cooperation with EUFIRELAB – FIRESTAR-2.0, FireRegime-1.0, SPREAD Section2, SPREAD Section2 WP, FireStation, FIRE LINE ROTATION MODEL (FRM), INCENDIU 1.0, SPREAD 1.0, AIRFIRE and DISPERFIRE.

One of the projects financed by the European Union is EFAISTOS. It constitutes the first part of the European behaviour model for forest fire, taking into account the lower layers of the forest fuels. Present In Valette et al. (1999) is presented a generic model of the experimental process, based on expert knowledge and experiments carried out within the framework of the European R&D project "Efaistos" (Environment and Climate Program, DG XII). This model can be used in some experimental fires and some real fires (prescribed burning and wildfires). It has been implemented within a Fire Behaviour Modelling Support System, aiming to constitute a database at the European scale. In order to assist the researchers in their activities related to the experiments, the researchers propose to design a prototype of Problem Solving Environment (PSE), called MODELLIS (MODELLing Information System), dedicated to the fire behaviour modelling support founded on terrain experiments.

PROMETHEUS is a Management Information System dedicated to forest fire protection. The project is realised in the frame of ENVIRONMENT and CLIMATE R&D Program of the European Union and was implemented by a Consortium of seven European research organisations co-ordinated by ALGOSYSTEMS s.A

1.3 Fuel Particle Characteristics

1.3.1 Description of Fuel Properties

Vegetation is assimilated to fuels for the purpose of predicting the behaviour of a fire, either relative (fire danger rating) or actual (rate of spread, intensity, flame size, etc.), as well as the impact of fire. Consequently, there exists an overwhelming variety of methods designed to study and describe fuel characteristics.

Fuel particles are the smallest elements considered in order to study the fuel structure. They are organs or pieces of the aerial parts (dead or live) of the vegetation: branches, leaves, barks, cones, needles, etc. Fuel particles are partitioned by size classes and their condition (live or dead), therefore establishing the limits for the description of their properties. Particle size categories are not standard across the world, which hinders comparability of fuel data and fire behaviour models. For fine fuels the limit value for diameter is 6mm.

Fuel particle characteristics contribute to the prediction of wildland fire intensity and severity, with all its consequences on suppression difficulty and human safety. Characterization of fuel particles is therefore required to interpret the results of flammability experiments in the laboratory and as an input to semiempirical and physical fire behaviour models.

Main types of characteristics of fuel particles are:

1. Physical characteristics:
   - ***measured physical characteristics: length, width, thickness, diameter, mass, volume;***
   - calculated physical characteristics: mass to volume and surface to volume ratios.

2. Chemical characteristics: moisture and chemical composition, ash content.
3. Thermal characteristics: thermal degradation and high calorific value.
4. Other: flammability.

The physical, chemical and thermal properties of fuel particles are assessed at the level of the individual particle or element (leaf, spine, stalk, twig, branch, stem, etc.), or of compounded particles belonging to the same biological entity, e.g. the assemblage of leaves and small twigs of a given shrub species.

Extensive search in biomass has been also made in order to assess the relative flammability of the species. Some authors use the term ‘inflammability’ as the ability of the fuel to ignite after having been submitted to calorific energy. This term coincides with the term ‘ignitability’ in the American literature. According to fuel flammability the species are ranked by using two properties – heat content and temperature of ignition (Dimitrakopoulos, 2001).

The following fuel properties affect the plant flammability:

- Heat content (calorific value) of a given fuel is a comprehensible measure of the potential thermal energy that can be released during the burning of the fuel;
- Total ash contents reduces the amount of combustible fuel mass, since only the organic part of the fuel supports combustion. Mineral (silica-free) ash is important during the early stages of pyrolysis by catalyzing the char formation reactions, thus reducing the flammable gases evolved.
- Surface area-to-volume ration is a meaningful measure of the fuel particle size since it determines to a great extent the heat and moisture exchange rates.
- Fuel particle density affects the thermal conductivity of the fuel and, therefore, its ignition time.

Various methods and procedures are available for sampling and for determining fuel characteristics. Presented underneath is an example based on data derived from L. Nunez-Regueira (1996).

For collection and preparation of the samples, 1 ha of woodland is chosen. The plots are divided into 1 m^2 size sites, five of which are randomly chosen. From every site, bulk samples consisting of bark, branches having a diameter not greater than 8 cm, fruits, leaves and in general all of the living parts of trees are collected. The bulk sample is reduces by coning and quartering procedure to a representative sample of about 1 kg. Part of the sample is used in the flammability experiments. The environment of the fuel samples is recorded and example is presented in Table 1.1.

Item	Data
Altitude	100–320 m
Annual rainfall index	1865 mm
Summer rainfall index	217 mm
Mean annual temperature	12.1 °C
Mean daily maximum temperature of the warmest month (June)	31.5 °C
Hydric deficiency	26
Mediterraneanity index	1.27
Representative species of the zone	*Pinus Pinaster* Aiton, *Eucalyptus globulus* Labill , *Sarothamnus scoparius* (L.), *Ulex europeas* L., *Rubus fructosus* L., *Pteridium aquilinum* L., *Castanea sativa* Miller, *Quercus robur* L., *Acer pseudoplatanus* L.

Table 1.1 Environment of the fuel samples.

1.3.2 Physical, Chemical and Thermal Characteristics

1.3.2.1. Methods for determining the vegetation particle characteristics

In their publication Allgower et all. (2002) present the basic methods for experimental determination of various characteristics of the vegetation bed in terms of using it as a fuel bed. The following presentation summarises these methods and is based on this report of EUFIRELAB.

The density of fuel particle is usually assessed by weighing ovendry particles and by measuring the volume of fresh, air-dry or oven-dry particles, although some researchers use fresh samples. Volumes are measured by immersion in mercury or in water, the most common choice. There is also another approach where the density is determined based on measurements of particle size and calculations of particle volume.

Determination of the surface area to volume ratio of fuel particles is possible by a variety of methods. Like with particle density, measurements can proceed in fresh, air-dry or oven-dry biomass. The most accurate solution for three-dimensional and long narrow particles is the measurement of the perimeter-area ratio of a cross section by photomicrography or image analysis. The most straightforward and used approach is to establish mathematical relationships between the physical dimensions of fuels and their surface and volume which rely on the description of shape by simple geometry Johnson (1984) propose a method for conifer needles based on simple geometry where the surface area is a function of needle length, number of needles per fascicle and volume displaced by water immersion

Various methods could be used to determine the moisture content of the fuel bed. The most commonly used one among them is based on measurements of vegetation mass before and after the drying process, and also on calculations of moisture content as the difference between the two values and then expressed relative to the mass of either the moist vegetation or the dried vegetation. The use of portable ovens, either based on microwave radiation or on the conventional method, can overcome the major problem of oven-drying, i.e. the time delay to obtain a result and its impracticability in the field. Chemical methods for determining the moisture content of the vegetation bed were also established and these involve, for example, the addition of calcium carbide to minced fuel samples in a pressure cylinder. The moisture content of the fuel bed can also be determined by measuring the electrical characteristics of the vegetation particle (capacity or electrical resistance) and using the relation between these quantities and the amount of moisture content.

Determination of ash content can be performed with the samples placed in a muffle furnace heated to temperatures higher than 300°C and up to 650°C, cooled down and then weighed. An alternative method for determining this chemical characteristic is to use a differential thermal and thermogravimetric analysis which involves the heating up of the fuel particle with a constant rate, and then measuring the temperature and the variations in the mass of the sample. These methods can be used for determining also the chemical composition (the amount of volatiles, etc.), and also to determine the rate of variation of the fuel mass.

Heat contents of fuel particles, whether high or low (i.e. corrected for the latent heat of water vaporisation) and with or without ash, are determined by standard adiabatic bomb calorimetry. The only alternative method has been developed by GILLON et al. (1997) and uses near-infrared reflectance spectroscopy.

1.3.2.2. Experimental data for Mediterranean pine species

Presented further are data for the characteristics of pine needles for vegetation species typical of the Mediterranean region. Most of the data is characteristic of a fuel bed made up of mainly dead vegetation particles. Table 1.2 provides data from experiments carried out using EUFIRELAB programmes for the countries along the Mediterranean for three major representatives of pine species – *Pinus halepensis*, *Pinus pinaster* and *Pinus brutia*.

Species	Heat content, [kJ/kg]	Total ash content, [%]	Silica-free ash, [%]	SA/V*, [m^{-1}]	Particle density, [kg/m^3]
Pinus brutia needles (Dimitrakopolous, 2001)	20 625	3.18	2.81	5554	310
Pinus brutia needles (Greece, Cohen 2001)	-	3.07	-	6730	559
Pinus brutia needles (Liodakis 2003)	21380	-	-	-	540
Pinus halepensis needles (Dimitrakopolous, 2001)	22137	3.94	3.52	6249	290
Pinus halepensis needles (Greece, Cohen 2001)	21200	-	-	10900	-
Pinus halepensis needles (Greece, Cohen 2001)	-	3.35	-	6980	835
Pinus halepensis needles (Spain, Cohen 2001)	21600	-	-	7780	519
Pinus halepensis needles (France, Cohen 2001)	22300	3.88	-	6050	742
Pinus halepensis needles (France, Cohen 2001)	22300	3.19	-	9170	-
Pinus halepensis needles (Liodakis 2003)	22185	-	-	-	450
Pinus pinaster needles (Portugal, Cohen 2001)	21400	-	-	4640	660
Pinus pinaster needles (Spain, Cohen 2001)	20500	1.16	-	3010	490
Pinus halepensis needles (France, Hernando 2002)	22331	3.61–3.88	-	6048–6167	706
Pinus halepensis needles (Spain, Hernando 2002)	22075	-	-	7973–8740	790
Pinus pinaster needles (France, Hernando 2002)	21198	1.16–2.55	-	2925–3061	490–652
Pinus pinaster needles (Spain, Hernando 2002)	21302	-	-	4824–4990	660

Table 1.2 Characteristic properties of pine species from different sources (in parentheses)

** surface area to volume ratio*, [*1/m*]

Pinus brutia and *Pinus halepensis* have high heat content, surface-to-volume ratio and very low ash content and particle density. Since plant flammability is favorably affected by SA/V and heat content the pointed species (*Pinus brutia* and *Pinus halepensis*) are considered *very flammable* (Dimitrakopolous, 2001). Pine leaves have smaller SA/V ratio then needles and greater mass-to-volume ratio (density). It is obvious from the results presented that variations in heat and ash content values for different sources are not substantial, while substantial differences are observed for surface-to-volume ratio and density. The latter could be due to different factors: the particular region where the study was performed, the season of the year, the moisture content of vegetation, etc. Small differences in heat and ash content could also be interpreted as a sign of very similar chemical composition of these vegetation species.

The tables underneath present data from studies on variations of fuel particle characteristics for Pinus pinaster (Nunez-Requerira, 1996). The studies have been conducted in the region of La Coruha (Galicia, Spain), for two different areas – Sada (coastal area) and Santiago (hillside and plateau area). These data were evaluated as a help for fighting forest fires, which have been very frequent in this region. Table 1.3 illustrates the variations in fuel moisture content (expressed as a percentage of the initial mass of vegetation particles), density and ash content. As it is rather normal to expect, the lowest moisture content is observed in sprint time, but high values (above 50%) should also be noted, most probably due to the fact that live foliage is studied and the area is very close to the Ocean.

Season	Moisture, %	Density, kg/m^3	Ash, [%]
Spring	56.30	650	1.04
Summer	53.50	640	0.84
Autumn	61.50	640	0.91
Winter	60.46	630	0.71

Table 1.3 Pine litter fuel properties at different seasons – Pinus pinaster needles.

When presenting the results on heat content variations throughout the year two calorific values are considered. The higher heating value (HHV) is defined as the quantity of heat generated by complete combustion, in a bomb calorimeter, of a unit mass of a sample in an oxygen atmosphere assuming that both the water contained in the sample and that generated from the combined hydrogen remains in liquid form. The lower heating value (LHV) can be calculated if it is assumed that the water in the products remains in the form of steam. Values for HHV and LHV are indicated in Table 1.4.

Season	HHV, [kJ/kg]	LHV, [kJ/kg]
Spring	19480.91	6524.90
Summer	20658.80	7646.12
Autumn	20463.05	5868.74
Winter	20398.48	6028.93

Table 1.4 Heating value of fuel as function of the season.

As expected these calorific values are highest in summer and lowest in spring. As was mentioned, this fact is related to the blooming period of most of the species, that Mediterranean Greece coincide with a season of frequent rain fall, so increasing their moisture content and diminishing their HHV. The experiments show that these values differ along the place of the probe, which is related with the variety of other species, i.e. trees and bushes with high calorific value in the appropriate zone. As can be seen *Pinus pinaster* has extremely high calorific power and also high flammability during the whole year. The great amount of essential oils and resins, combined with a HHV and the high inflammability of this species, places it in the group of high-risk trees because of its readiness to start and spread forest fires.

Wood can be chemically analysed by breaking it down into structural components (called proximate analysis) or into chemical elements (ultimate analysis). The main structural components are Cellulose, Hemicellulose, Lignin and ash. Volatiles and solid carbon (char) are generated in the process of heating-up the fuel. Carbon and oxygen are the main chemical elements constituting almost 90% of the vegetation contents.

Nunez-Requerira (1996) also presents data on the chemical composition of *Pinus pinaster.* The chemical analysis (ultimate analysis) of vegetation species is presented in Table 1.5.

Season	**Chemical analysis [% of total composition]**						**Volatile metals [ppm]**				
	N	C	H	O	S	Cl	Cu	Cd	Zn	Pb	Mn
Summer	2.25	50.13	6.54	40.46	0.10	0.52	52.34	1.94	19.40	6.78	6390.00
Autumn	1.90	44.64	5.71	47.46	0.22	0.067	6.13	2.30	17.48	1.86	83.12
Winter	1.65	48.10	7.31	42.83	0.06	0.05	4.32	2.88	11.53	0.90	92.24
Spring	3.02	46.96	6.39	43.41	0.22	-	0.29	1.60	25.60	2.10	1206.30

Table 1.5 Ultimate analysis and volatile metal analysis of Pinus Pinaster.

As can be observed from the table, the composition of the fuel does vary in small ranges during the year, but generally the chemical composition could be considered constant (Mathieu, 2002; Viegas, 2001). Furthermore the fuel shows its highest flammability in the summertime and lowest in spring and winter as expected. These last values relate to the high degree of humidity of the species in these seasons. The observed high contents of Mn, compared to other elements can be explained by the need for this ion in the transportation from the water to photosynthesis areas.

For comparison proximate and ultimate analysis of some other biomass fuels are presented in Table 1.6.

Fuel	**Ultimate analysis [% of total composition]**						**Proximate analysis**				
	C	H	O	N	S	Cl	Moisture, wt% wet fuel	Ash, wt% dry fuel	Fixed C	HHV [MJ/kg]	LHV, [MJ/kg]
Clean wood	49.10	6.00	44.30	0.48	0.01	0.10	50	1.3	13.2	19.2	15.4
Bark from spruce	51.10	6.04	42.40	0.41	0.03	0.03	55–65	2.34	22.46	19.83	18.54
Straw from wheat	49.60	6.16	43.50	0.61	0.07	0.18	55	4.71	17.59	18.94	17.65
Grass reed canary	49.40	6.25	42.70	1.54	0.15	0.07	60	8.85	17.65	18.37	17.13
Waste–demolition wood	48.80	5.25	45.60	0.15	0.03	0.08	15–20	0.9	-	15.4	13.9
Salix	50.30	6.17	43.1	0.40	0.03	0.004	50	1.18	18.92	19.75	18.42

Table 1.6 Comparative table for the properties of different biomass fuels.

Additional data for the chemical composition of the pine needles is presented by Ucar (2004). This data reveals the chemical complexity of the fuel, the needles, the branches as well as other components of the fuel, so the expected chemical reactions set will consists of hundreds of reactions, which are not applicable in an engineering approach to model a wild fire behaviour. Furthermore, the composition of the released light gases (volatile gases) as well as released tar varies with the environment conditions (Barnola, 2000; Owen, 2002; Dormont, 1998; Piccardo, 2005) – temperature of the fuel particles, intensity of heating rates to/from the fuel, gas composition environment (mainly the partial pressure of the oxygen). Obviously the presented, strongly time dependent process can not be described in deep details in any of the available biomass combustion models, both because of the uncertainty of the initial and boundary conditions as well as the fuel properties, and the complexity and uncertainty in the chemical reactions and their rates.

As can be seen the variety of biomass fuels presents close range of fuels properties variations, thus revealing opportunity to develop a common model for biomass combustion (Carvalho, 2002; Jones, 2000; Demirbas, 2004), based on the appropriate physical properties and chemical composition of the fuel (Owen, 2002; Dormont, 1998). This will be used to develop a model, based on data for different biomass materials in case of lack of specific information for items of the developed model. For example the HHV could be calculated, based on the ultimate analysis as follows:

$$HHV = \frac{1}{100.0}\left(34.1C + 102H + 6.3N + 19.1S - 9.85O\right), \text{ [MJ/kg dry fuel]} \tag{1.1}$$

Fletcher (2000) proposes a formula, which is used to calculate the HHV of the biomass fuel as follows:

$$HHV = 2.32\left(146.58C + 568.78H - 51.53\left(O + N\right) - 6.58\,Ash + 29.45\right), \text{ [kJ/kg]}, \tag{1.2}$$

where C, H, O, N and Ash – weight percentage on the dry basis.

Another formula (Fagbemi, 2001) is proposed by Institute of Gas Technology (IGT), in which the amount of the elements, C, H, O, N and Ash, are expressed in mass fractions:

$$HHV = 354.68C + 1376.29H + 71.26 - 15.92\,Ash - 124.69(O + N) \text{ [kJ/kg]}, \tag{1.3}$$

Actually the HHV for pine litter fuel is available and the presented formulas could be used for validation and verification purposes as well.

1.3.3 Ignition Temperature and Flammability

The second phase (after pyrolysis) in the burning process is exothermic and it is known as combustion. Combustion may be with or without flame. Flaming combustion is a gas oxidation phase, accompanied by emission of flames. It takes place when the temperature of volatiles, emerging through the surface of the forest fuels, reaches 450–500 °C. Liodakis (2002) presents data, according to which the minimum surface temperature (critical surface temperature) of wood under radiative heating mode for spontaneous ignition is 600 °C and for piloted ignition 300–410 °C. With convective heating the spontaneous ignition, occurred at 490 °C and with piloted ignition 450 °C (Dormont, 1998). From the literature is shown that both the minimum pyrolysis rate and the minimum surface temperature can be used as criteria for ignition. However, from a practical point of view, the surface temperature criterion is much more convenient.

This same report also presents results from experiments for ignitability properties for *Pinus halepensis* and other vegetation species characteristic for the particular region of Greece. Form these we also observe that an ignition temperature of 480 °C was defined for *Pinus halepensis*. Moreover, the generation of volatiles begins at temperatures above 200°C and it reaches its highest intensity in the range of 320–370 °C. When a temperature of 500°C is reached, the generated amount of volatiles constitutes around 55% of the initial mass of the sample material.

Flammability (the ability of species to ignite and sustain fire) ranking of forest species is an essential component of fuel hazard and fire risk assessment. Dimitrakopoulos (2001) presents some studies of above-mentioned vegetation species characteristic for the particular region in Greece. *Pinus pinaster* and *Pinus brutia*, which dominate the composition of pine litter, have been classified as "Extremely flammable". Table 1.7 presents appropriate ratings according to the flammability index (L. Nunez-Regueira, 1996).

Index	Flammability
0	Very low flammability
1	Low flammability
2	Flammable
3	Moderately flammable
4	Very flammable
5	Extremely flammable

Table 1.7 Flammability index.

Table 1.8 illustrates the seasonal variations in the flammability index of *Pinus pinaster* throughout the year (L. Nunez-Regueira, 1996). The expected highest fire risk is during the summer. Generally, from this data it can be seen that pine species are extremely flammable and fires occurring in such vegetation species are usually highly intensive and carry a high degree of risk.

Flammability values of Pinus Pinaster				
Season	Spring	Summer	Autumn	Winter
Index	4	5	4	3

Table 1.8 Flammability of Pinus pinaster at different seasons.

1.3.4 Development of Fuel Models – Basic Characteristics

Fuel complexes result from the organization of fuel particles into a microstructure, which can result of single, or multiple beds or layers.

Fuel group is a complex of fuel elements with average properties values representative of the typical fuel conditions (combustible materials) of a certain vegetation type (Dimitrakopoulos, 2002). It is also a set of quantitative fuel inputs to fire behaviour models.

A major characteristic feature of the fuel group is fuel load – the dry weight of fuel per unit area, [kg/m^2]. The structural arrangement of fuel particles within a fuel complex is essentially defined by porosity, particles orientation, and vertical distribution. Porosity is the ratio between the void volume in a fuel complex and its surface area. Fuel depth equals fuel height in grassy or shrubby fuel layers, but if the fuel complex includes a litter bed (usually not entirely available to burn actively in the fire front), a more objective definition of fuel depth is the vertical extent of the combustion zone.

Particles orientation and vertical fuel distribution are not explicit factors in fire models.

According to the classification undertaken in Dimitrakopoulos (2002), 7 fuel models were defined for the region of Greece. Dominant species for fuel model 7 (forest litter layer) are *Pinus Brutia and Pinus Halepensis.* Other models are for medium to high shrubs and one model is provided for grassland. Fuel models 1–5 include the following vegetation species *Pistacia lentiscus, Quecus coccifera*, *Arbutus unedo*, *Plomis fruticosa* and *Sarcopoterium spinosum*.

The methodology for the grouping of categorically equivalent species into fuel groups in Greece consisted of the following steps:

1. All areas covered with Mediterranean vegetation in Greece were stratified on vegetation maps according to the dominant vegetation type: grasslands, phrygana (small, xeric shrubs up to 0.5 m height), maquis (evergreen-broadleaved, sclerophyllous shrubs, 0.5–3 m height), or closed-forest litter of Mediterranean pine species (*Pinus brutia* and *Pinus halepensis*), the latest of main interest in this work.
2. In every representative location, 12 fuel parameters are measured in 500 m^2 sampling plots. The clip-and-weight method is used for the determination of all fuel loads by size category. The line-intercept method is used in order to estimate the area cover by each vegetation type. All fuel loads (fuel weight per unit surface area) are expressed on a dry-weight basis.
3. The collected data are subject to statistical analysis.

Fuel categories for the region of Greece drawn up by Dimitrakopoulos (2002: 128) can be divided into three separate groups:

- Shrubs of average height between 1 and 2 meters – the first three models;
- Shrubs of average height between 0.4–0.55 meters – the Phrygana I and Phrygana II models (here we also include the grasslands model);
- Litter representing models –Pine forest litter.

At present we are interested to develop the conditions for the burning of Pine litter. The literature survey shows that the forest litter of Mediterranean pine species has the properties, presented in Table 1.9. The chemical composition of the pine needles will not be presented here, but can be seen in Ucar (2004).

Forest litter of Mediterranean pine species								
Average height, [cm]	Branch diameter, [cm]			Litter depth, [cm]	Litter weigh, [t/ha]	% cover by litter	Dry pine needles, [t/ha]	Fallen tree-branches, [t/ha]
	0.0–0.5	0.6–2.5	2.6–7.0					
1.5	70 %	20 %	10 %	6	12.55	100	10.2	2.35

Table 1.9 Properties of forest litter of Mediterranean pine species

The distinct morphological differences of the two dominant phrygana species in Greece resulted in two separate fuel models with different geographic distribution. The low-elevation Mediterranean grasslands and the litter of closed pine forests demonstrated limited spatial heterogeneity and are represented by a fuel model each. The fuel model for pine forest litter considers total load of 12.55 t/ha. Due to the fact that the experiments for the fuel properties determination are held in the summer period, most of the grassland fuel load was allocated to the dry fine fuel category. The litter load of the Mediterranean closed forests of *Pinus Halepensis* and *Pinus Brutia* (*Calabrian pine*) comprised mainly dry pine needles (10.2 t/ha) with a small proportion allocated to the fallen tree-branches (2.35 t/ha) of the forest floor. Experiments show that severe burning conditions are observed in the forest litter despite the compactness of the litter layer (litter depth 6.0 cm). It should be emphasized that the local fuel conditions may vary from one area to another, thus the presented fuel model may substantially vary according to the fuel data.

1.4 Theoretical Modeling of Fire in Vegetation Layer

1.4.1 Classification of Fire Behaviour Models

Various systems for classification of models used to predict surface fires' behaviour are available. One of these classification systems groups the different models according to the predicted characteristics (Grishin, 1997):

- models used to predict the rate of spread (ROS) of the fire;
- models used to predict the outlines of the forest fire;
- models used to predict the flow characteristics, the heat transfer and mass transformations along the fire front and inside the fire zone;
- general mathematical models within which all characteristics could be predicted (rate of spread, outlines of forest fires, temperature range, component concentration and velocities distribution) along the fire front and inside the zone of the forest fire.

Depending on the approach adopted in the development of the models used to describe the behaviour of forest fires, including that of surface fires, two basic groups of models were formed: stochastic models and deterministic models. Stochastic models consisting to predict the more probable fire behaviour from average conditions and accumulating acknowledges obtained from laboratory and outdoor experimental fires. Deterministic models in which the fire behaviour is deduced from the resolution of the physical conservation laws (mass, energy, momentum) governing the evolution of the system formed by the flame and its environment

The main purpose of these models is to predict the local rate of spread of a fire front, when parameters characterising the condition of spread (vegetation, meteorology, terrain) are given.

It is reminded that stochastic models are only based on the observation of field fires (experimental fires and wildfires) from which the fire rate of spread (ROS) is related to relevant parameters in a purely statistical way (fuel type, fuel loading, fuel moisture, wind). These empirical relations depend strongly from the very specific conditions from which the statistical study was performed. Without systematic parametric studies, it is very difficult to extract a general behaviour for the fire.

The most commonly used classification of fire behaviour models groups the latter into three basic categories: empirical (or statistical), semi-empirical (semi-physical or laboratory models), and physical (theoretical or analytical) (Morvan et.al., 2003). The purpose of physical modelling of fire behaviour is to obtain a mathematical solution to the complex mechanism of the occurrence and spreading of forest fires (Andrews, 2001). Formulating an accurate theoretical model capable of providing a reliable description of fire behaviour that is of certain practical value requires multiple combinations of input conditions (to comply with actual ones) and powerful computing resources.

At present, fire modelling for operational applications is basically addressed to the establishment of semi-empirical or empirical models.

1.4.2 Empirical Models

Empirical fire behaviour models are based on data collected in experimental fires or in well-documented wildfires or prescribed fires (Bachmann, 2001). Empirical models are built by correlating the observed fire characteristics with easily measured variables, which describe the so-called fire environment (fuel, weather and slope). The process of building up is governed by observations and statistical evaluation of forest fires with interrelations taking account of theoretical knowledge (Pastor et al., 2003).

Some of the advantages of empirical fire models are:

- The absence of artificiality and scale problems (present in the lab experiments associated to physically-based models);
- The integration of numerous factors, which operate in the real world, such as wind and moisture profiles (impossible to reproduce in the lab) and fuel heterogeneity.

The disadvantages of these models are:

- They are basically built upon experimental data and are not to be used in conditions that are different to the ones they are meant for;
- Various reasons of economical, practical and other nature virtually limit the possibilities for experiments corresponding to real conditions, thus reducing the capabilities of built up models;
- The empirical models thus created are single-dimensional and unalterable.

According Mendes-Lopes (1998) the future will hopefully bring more fundamental solutions but, for the time being, the most apparent benefit of a physical approach to fire modelling is its contribution to understand fire propagation mechanisms, therefore helping the experimental design and interpretation of field trials.

1.4.3 Semi-Empirical Models

Semi-empirical models represent a further development of empirical models and they usually comprise one basic equation describing the energy balance and involving the basic (or some of the basic) heat transfer methods: radiation, convection and conduction. The heat transfer processes involved are described by submodels (Catchpole, 2002), which are largely empirically derived and associated to the type of fuel and the region involved (Simeoni, 2002). This is what lessens the universal application of these models. Semi-empirical (semi-physical) models are largely single-dimensional or two-dimensional models. When such models are to be created it is necessary to establish a balance between universal application characteristics and the complex design of the model (Mandel, 2004).

One of the most common semi-empirical models is the Rothermel model (1992). It is based on physical principles but also involves a number of parameters derived from laboratory experiments or from field data from Australian grass fires. The physical grounds for this model provides possibilities to use it within a wide range of conditions and also to achieve good results in predicting fire behaviour. However, according to Catchpole (2002) some of the drawbacks of the Rothermel model include its super sensitivity to the height (depth) of the vegetation bed and low efficacy in predicting fire behaviour in vegetation bed comprising a large amount of "live" components.

Another widely used model is the BEHAVE fire prediction system. This is a computer fire simulation program that uses as inputs the fuel, weather and topography properties to calculate quantitative fire parameters – rate of fire spread, fire line intensity and flame length (Andrews, 1986). Behave equations are also based on mathematical and physical laws of thermodynamics and heat transfer. To reflect its expanded scope, it is now called the *BehavePlus* Fire Modeling System (Andrews, 2005).

Dimitrakopoulos (2001) uses the Behave model to design the Novel nomographs for determination of fire behavior characteristics for developed fuel model. Combustion models are made up of vegetation species characteristic of the Mediterranean and are considered representative of the region of Greece.

The following semi-empirical equation are basis for determination of ROS with using of BEHAVE software:

$$\mathrm{ROS} = \frac{\mathrm{I_r}\xi(1+\phi_w+\phi_s)}{\rho\varepsilon\mathrm{Q}}, \text{ [m/min]} \tag{1.4}$$

From this equation can be see that ROS is affected by the next factors: fire reaction intensity I_r – rate of heat release per unit area of flaming fire front, propagating flux ratio ξ, fraction of total heat released from the flaming front that is absorbed by adjacent unburned fuels and depends on the geometrical properties of the fuel bed (surface area/volume ratio of fuel particles, wind factor Φ_w, and slope factor Φ_s, the effects of wind speed and slope on the rate of fire propagation, porosity of fuel bed ρ, effective heating number ε, fraction of total fuel load that is heated to ignition temperature, heat of pre-ignition Q – heat required to bring a unit mass of fuel to ignition temperature. The last factor heavily depends of fuel moisture content.

The rate of heat release per unit length of flaming front (fire line intensity I) is dependent on surface load SL and heat content of vegetation fuel H and it is determined using the the following equation:

$$\mathrm{I} = \mathrm{SL} \times \mathrm{H} \times \mathrm{ROS}, \text{ [kW/m.s]} \tag{1.5}$$

The equation used to determine the length of the flame L_f shows that the latter is modelled as a function of fire line intensity:

$$\mathrm{L_f} = 0.45(\mathrm{I})^{0.46}, \text{ [m]} \tag{1.6}$$

Another commonly known system used to predict the fire behaviour for surface fires is FARSITE (Finney, 1994). The FARSITE is computer program that uses Huygens' principle of wave propagation to expand fire fronts. In general, Huygens' principle enables a logical implementation of existing fire behaviour models. Each point on the fire front contains information on the time, direction, and rate of fire spread. These are essential components of existing models of surface fire spread, fire acceleration, crown fire and transition to crown fire, as well as spotting. Fire spreads more rapidly in the direction of the wind and the direction of upslope, so an ellipse is often used to quantify the shape of a point source fire.

FARSITE incorporates models for surface fire spread (Rothermel, 1972; Andrews, 1986) as well as transition to crown fire and crown fire spread. The FARSITE model requires the user to identify the data files (containing landscape, weather, and wind data). The mouse is then used to input ignitions on the displayed landscape. These ignitions can be points or existing fire shapes (drawn as a series of line segments). In a similar fashion, users can make minor modifications to the landscape including control lines or fuel type changes. The duration of the simulation is determined by either time elapsed or defined by the desired ending date and time. The model requires the support of a geographic information system (GIS) to manage and provide landscape data.

The FlamMap fire behavior mapping and analysis system fills a need not met by either FARSITE or BehavePlus (Finney, 2006). It uses the spatial fuel and terrain data that is used by FARSITE and implements fire models that are in FARSITE and in BehavePlus. The focus of FARSITE is to simulate fire growth and the changes that occur over time for a specific fire. FlamMap is a spatial implementation of the point models in BehavePlus without the simulation techniques required by FARSITE; each point on the landscape is an independent calculation. A map is produced for an area of any modeled value such as flame length. Comparisons can be made between locations, or the effect of fuel treatment can be examined. Like FARSITE and BehavePlus, FlamMap is a PC based program designed for use by local fire managers.

In Catchpole et all. (2002) is presented a semi-physical model for the steady spread of fire through a homogeneous fuel bed. The fuel bed is modelled as an arrangement of homogeneous particles all with the same moisture content at ambient temperature. The role of the air between the fuel particles is to supply oxygen and the thermal capacity of this air is neglected. The diagram of the computational range is presented in Figure 1.1. The model is based on a physical representation of the heat transfer processes. The heat from the fire flame is transferred to a cell into the fuel bed based on the radiation from the flame and the convection resulting from the hot air. The cell in the vegetation layer increases its temperature and ignites when it reaches the ignition temperature (a pre-assumed value) and eventually becomes a source of heat. The temperature distribution in the fuel bed is derived based on a simple differential equation presenting the thermal energy balance for a surface volume element from the fuel bed. When the flame reaches the volume element, the temperature reaches ignition temperature and the volume element bursts into flame. This is often referred to asan integrated or global energy balance.

The flame height and flame angle are function of Byram's fireline intensity (Byram, 1959) and wind speed. In cases where the wind velocity in the fire zone is zero, the flame height is equal to its length and this characteristic is a function of only the fireline intensity.

The temperature profile in front of the fire front is modelled by a reducing exponential law of a maximum value along the line of the fire front. The maximum temperature is derived based on an exponential relation and is a function of the surface area to volume ratio, wind velocity and fuel bed packing ratio.

This model can be viewed as a bridge between semi-empirical (semi-physical) models and prediction tools based entirely on physical laws for the preservation of mass, for the amount of movement and energy.

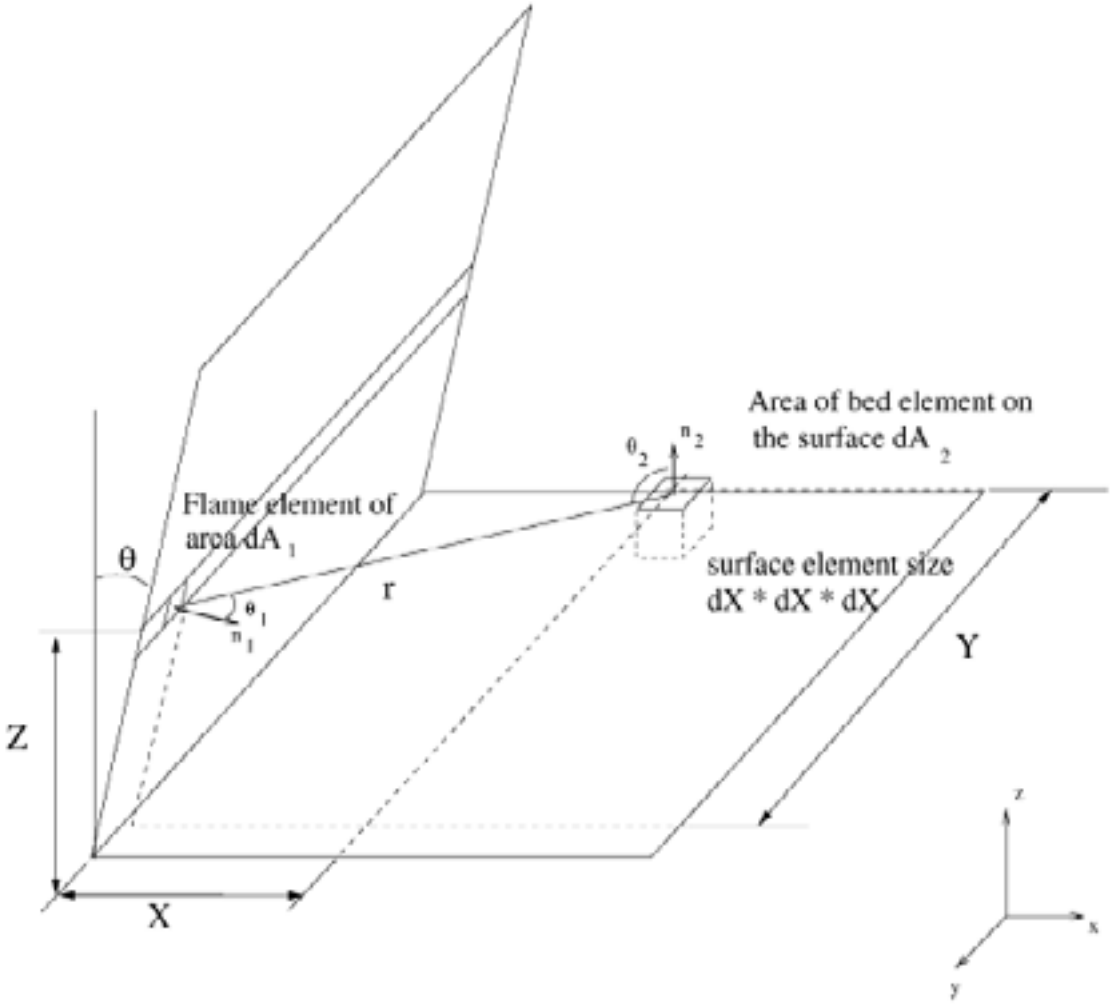


Fig.1.1 Schematic diagram indicating position of the fuel element on the surface of the bed. (Adapted from Catchpole et all. (2002))

Simeoni et all. (2002) present a semi-physical model for determining the surface area occupied by the fire (the position of head fire front and rear fire front) as a function of time. The report also presents results for a fuel bed comprised of *Pinus pinaster* needles from the region of Portugal. The basic equation presents a non-stationary variation in the vegetation bed temperature and is based on the balance between the thermal energy emitted and absorbed by the corresponding computational cell. Heat generation is a function of the heat content of the vegetation layer and an exponential law for the variations in the mass of the vegetation bed. The parameters of this law have been determined experimentally based on intentionally fired fires into a aerodynamic tunnel. The presented model takes into account the effects of air flow velocity and the slope of terrain on fire behaviour characteristics. An additional member was added to the model in order to take into consideration the effects of the slope of terrain and this member represents a radiational heat source and involves a parameter which is a function of the flame tilt angle, the emissivity of the flame, the absorptivity of the fuel, and the view factor. This parameter is presented using an empirical relation and experimentally determined values for the constants involved in it.

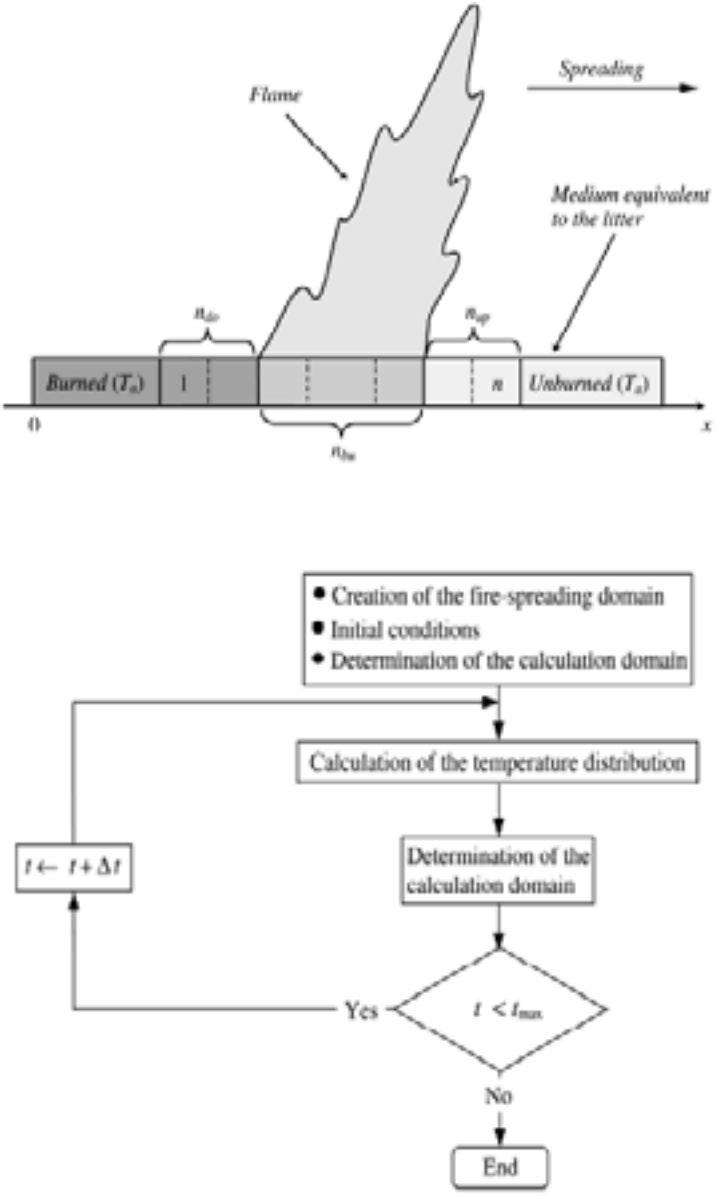


Fig. 1.2 Diagram of the computational area (on top) and an algorithm for the calculation of the outlines of the fire (Simeoni et al., 2002).

1.4.4 Physical Models

Physical models consider various types of heat transfer and recently (in the latest approaches) a multi-phase medium is employed to describe the fire. The said medium comprises one fluid phase and a number of solid phases and a detailed description of thermodynamic processes and fluid flow (with appropriate equations) is provided (Morvan, 2002a: 4–6). The implementation of these models and obtaining accurate results requires fast computing equipment, availability of specialised application software (or custom-made software) incorporating relevant mathematical models complying with the specifics of the physical processes involved, and is highly time consuming (Linn, 2002).

The next section of this literature review provides an overview of the major characteristics and peculiarities of a fire behaviour model of this type – physical.

1.4.4.1. Modelling of vegetation layer

In some physical models the vegetation layer is presented as a porous media (Zhou et al. 2000, Paz et al., 1998). In this case the processes considered involve the burning of one solid phase, representing the vegetation layer, and one gaseous phase. When no fire is present the gaseous phase is an air medium, and when a fire is started into this medium the result is the generation of the products of thermal decomposition of the fuel and the subsequent oxidation associated with the burning of the vegetation layer. In this particular approach the vegetation fuel bed represents a heterogeneous system made up of a solid matrix with a randomly orientated structure. In a small test amount the solid phase coexists with the gas phase and a simulation of the processes of interaction between the vegetation particles and the gaseous flow is made. The porous medium is in general considered a fluid zone with static solid vegetation particles present in it. The porosity of a gas phase is defined as the ratio of the volume occupied by gas to the entire volume of vegetation layer. In the similar way the packing ratio of solid phase is the ratio between volume occupied by solid phase and entire volume.

Solid vegetation particles exercise resistance to the gaseous flow and reduce its velocity within the fuel bed. The drag forces are described by means of adding a source term to the standard equation for the fluid medium. The source term is composed of two parts: a viscous loss term and an inertial loss term

For low-speed flows and laminar flows, the pressure drop is typically proportional to velocity and Darcy's Law:

$$\nabla p = -\frac{\mu}{\alpha}\vec{v} \tag{2.7}$$

At high flow velocities, the constant representing inertial resistant factor provides a correction for inertial losses in the porous medium. This constant can be viewed as a loss coefficient per unit length along the flow direction, thereby allowing the pressure drop to be specified as a function of dynamic head.

Coefficients accounting for pressure drop are directly dependent on the porosity **γ**. A number of dependencies exist to represent the relation between vegetation bed characteristics and these coefficients and the major part of them were derived based on experimental data. In Garzon (1997) permeability is expressed in the following way:

$$\alpha = \frac{D_{p2}^2 \gamma^3}{180(1-\gamma)^2} \tag{2.8}$$

$$D_{p2} = \frac{\int_0^\infty D_p^3 . f(D_p) . dD_p}{\int_0^\infty D_p^2 . f(D_p) . dD_p} \tag{2.9}$$

In these equations D_p is the average particle diameter and $f(D_p)$ is a function of the distribution L is the bed. These dependencies are basically applicable to spherical shape particles (which is different to the type of medium being considered here) but they can also be used for a wide range of tasks (Garzon, 1997). The following expression is used to describe inertial pressure drop:

$$p_{inl} = c_F \alpha^{-0.5} \rho v_{mag} v \tag{2.10}$$

In the above equation c_F is a friction factor and it is equal to 0.5 (Garzon, 1997).

An expression for the drag coefficient (C_D) in a bed of pine needles (*Pinus pinaster*) has been developed from Ventura (2002), using as parameters the bed porosity, the airflow velocity and temperature:

$$C_D = (-0.1546 U_{needles} + 1.3971)\left(0.5087\left(\frac{T}{293}\right) + 0.4913\right) \tag{2.11}$$

This expression is valid for the range of parameters covered by the set of experiments, namely

Porosity: $0.92 \leq \varepsilon \leq 0.94$

Flow velocity: $1.15 \leq U$ needles [m/s] ≤ 2.48

Flow temperature: $293 \leq T\ [K] \leq 337$

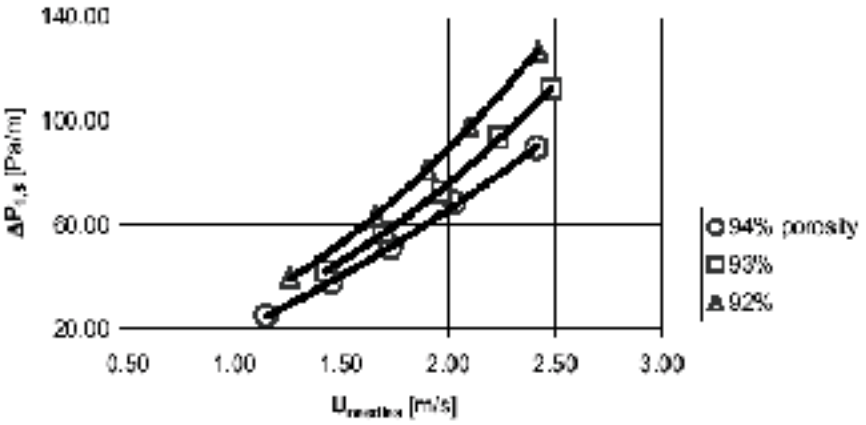


Figure 1.3 Pressure drop along the work module, as a function of air flow velocity, for 3 different values of porosity (VENTURA et al., 2002)

This expression can be useful in existing mathematical models for the prediction of surface fire propagation. Above results may be used to determine the resistance of the fuel bed. The resulted pressure drop data is presented on the Fig. 1.3.

Morvan et al.(2002) present a model of surface fires in shrubs and grass layer and the vegetation is presented via *n* number of solid phases and one gas phase. Each solid phase is represented as a mixture of dry material, water, charcoal and mineral residue (ashes).

This particular approach of presenting the vegetation layer is also used in the multiphase model described by Simeoni et al. (2002).

1.4.4.2. Mathematical models

In Morvan et al. (2002) a grouping has been carried out and the basic features of various approaches have been presented for the physical modelling of the fire behaviour for fires occurring in a bed of vegetation. Major attention has been paid to models based on a multi-phase medium (involving multiple solid phases) and also models where the vegetation layer is considered as single-phase discrete medium (and in some cases a porous media).

In the approach presented by LARINI et al. (1998) PORTERIE et al (2000), MORVAN et al (2000, 2001, 2002, 2003) the combustible medium is considered as a multiphase medium composed of a gaseous phase and several solid phases. Each solid phase consists of the same fuel particles, which have the same shape, the same size, the same physico-chemical properties, thus the same behaviour with respect to a fire. In particular, each family of particle is characterised by its surface-to-volume ratio and in order to achieve a spatial description of the medium, the fraction of space volume occupied by each family or each solid phase, at each point and each time, must be known.

In the approach of SÉRO-GUILLAUME et al. (2002), the vegetal phase is considered as a fractal medium, which can be described mathematically. Moreover the different parts of plants are considered as a porous medium (Zhou et al., 2000), in order to take into account the internal structure of vegetation.

When the fire approaches the particle it receives energy from this fire by convection and radiation. Its temperature is then raised from the ambient temperature up to the boiling water temperature, at which it looses its water. Subsequently, the temperature rises again and the plant material is decomposed step by step releasing pyrolysis gases. The reactive part of these gases is combined with the oxygen in the air (gaseous phase chemical reactions). The gas temperature then increases, causing its expansion and, due to buoyancy forces, the gas moves. These movements play a very important role in the necessary transport of oxygen and also in the energy transfers. At the end of the pyrolysis, the particle is mainly composed of chars. Oxygen may reach the surface of the particle and react with the remaining chars. It's the combustion of chars, which causes the regression of the particle surface.

The description of the medium is based on determining the parameters of the gaseous phase velocity, temperature, mass fraction of chemical species and pressure, as well as on determining temperature, mass fraction of chemical species and density at each point of the motionless particle.

At this scale, in order to calculate the state of the medium at each point of the gas, the balance equations of reactive fluid mechanics are available (mass, momentum, energy and chemical species) and at each point of the particle, a system of balance equations mass, chemical species, energy) is available, which describes the behaviour of a solid conductive medium that can loose its water and be decomposed into pyrolysis products. In addition, at the interface between the solid particle and the gas, some conditions must be verified (local interface conditions).

Solving all these equations at this scale can be done only in very simple geometric configurations, but cannot be done in real configurations with numerous particles distributed in a gas. In this last case, and at this scale, it is impossible to obtain solutions of the strongly coupled balance equations at each point of the gas, each point of each particle, which in addition must verify all local interface conditions.

Thus, it's necessary to change the scale of observation, in fact, to increase this scale. From a mathematical point of view, operating this change of scale is equivalent to average the equations established at a point of the gas or at a point of the particle over some volume around these points. It's a usual operation for modelling multi phase multi constituents materials and several methods of averaging are available.

After some mathematical transformations, a system of equations is obtained for each phase (gaseous phase and solid phases). These equations establish the relations in time and space between the weighted average of the different variables (temperature, velocity, density,…). It is worth noting that the averaging operation leads to the appearance of new terms in the balance equations, which are due to the interactions between the different phases (here between the gaseous phase and each solid phase). Thus, systems of partial derivative equations are obtained that are strongly coupled through these terms of interaction. For instance, these terms of interaction are due to the mass transfers related to the drying and pyrolysing process of the particles, to the drag forces, to the heat transfers by convection and by radiation. system of multiphase, reactive and radiative equations, rigorously deduced from the instantaneous point equations (generalised NAVIER-STOKES equations for the gas and point balance equations for the solid), is now available.

The interaction between the continuous and the discrete phase is described mathematically in several basic ways. Source terms are added to the equation describing the preservation of the mass of the gaseous phase and these are used for the modelling of the moisture evaporation (in the form of water vapour) and the release of volatiles from the vegetation layer. To maintain the mass balance for the entire area being considered, a variable mass of the solid phase is also modelled. Moreover, some authors also assume constant density of the vegetation particles throughout the pyrolisis process (Zhou et al. 2000), while other models consider a reduction in the density of the solid phase as a result of moisture evaporation and release of volatiles, and the volume occupied by this solid phase stays constant (Marcelli et al., 2004).

Turbulence processes in the continuous medium are modelled mainly based on the k – ε turbulence model or RANS models, but there are also other approaches, such as using large eddy simulation (LES) (McDonough et. al., 2004, Hostikka et al., 2001).

1.4.4.3. Modelling heat transfer

With the physical approach used for modelling fire behaviour it is especially important to consider the various processes of heat transfer within the gaseous medium and the vegetation medium both individually and between them. These types of models also give consideration to the three types of heat transfer (conduction, convection and radiation) and it is especially important for the spreading of the fire to consider the transfer of hot air from the fire zone and the heat radiation from the fire flame. The heat transfer via conduction heat transfer is of significance for vegetation layers of high bulk density (forest litter) in the direction of the depth of the vegetation layer.

Zhou et al. (2000) express the thermal interaction between the gaseous phase and the solid phase for pine litter using the following convective/conductive heat flux:

$$Q_c = Ah_c(T - T_s) \tag{1.12}$$

In the above relation A is specific wetted area and this is proportionate to the surface to volume ratio of the solid phase, T и T_s are the temperatures of the gaseous phase and the solid phase, respectively. The heat transfer coefficient is deduced from Nusselt number of solid phase

$$Nu = \frac{h_c d}{\lambda_s} = 0.683\,Re^{0.466} \tag{1.13}$$

In above equation λ_s is thermal conductivity of solid phase.

The important mechanism for heat transfer from the flame zone is radiation. The radiation heat flow from the high temperature zones is a function of the absorption coefficient of the medium a, the Stefan – Boltzmann constant σ, and is proportionate to the fourth degree of the temperature of the emitting body. For the particles inside the vegetation layer located close to the fire flame the increase in temperature is mostly dependent on the amount of heat they absorb as a result of the radiation heat transfer. The expressions for the radiation heat sources for the gaseous phase and the solid phase are determined as follows (Zhou et al., 2000; Johnson et al., 2001):

$$Q_{rad,g} = \xi_g . a_g (4\sigma T^4 - G) \tag{1.14}$$

$$Q_{rad,s} = \xi_s a_s (G - 4\sigma T_s^4) \tag{1.15}$$

The indices g and s in (1.14) and (1.15) above are used to indicate the parameters of the gaseous phase and the solid phase. The absorption coefficient for the vegetation layer is calculated using the standard formula $a_s = A/4$ (Porterie et al., 1998). For pine litter featuring high values for wetted area A the thermal flow from the flame radiation will affect the temperature rise inside small depths of the vegetation layer. Thus, a conclusion can be drawn that the convection heat transfer and the radiation heat transfer from the fire zone are especially important for the increase in the temperature at the surface of the vegetation bed. Major role for the temperature rise of the vegetation layer at locations close to the fire flame plays the heat radiation, and as the distance from the fire flame is increased, the effect of the hot gas convection becomes more significant.

The absorption coefficient of the gas phase is related to the concentration of combustion products (CO_2, H_2O) and soot formation (Kaplan et al., 1996). According to Marcelli et all. (2004) "The chemical nature of the burning material and local specific fire conditions can lead to a large production of soot" and also "An accurate prediction of radiative transfer requires accounting for soot production/destruction, especially in turbulent flames".

1.4.4.4. Modelling the heat generation

For the burning process to occur and persist, it is necessary to have heat generation in order to heat up the surrounding vegetation and cause the release of combustible gases, which release additional amount of heat as they undergo further oxidation. Thus, two steps are identified during the process of heating up the vegetation layer: the first one is a endothermal process of heating up and evaporation of moisture and release of volatiles, leading to subsequent oxidation accompanied by exothermal heat generation and continuing temperature rise.

In the course of the modelling two groups of models can be identified depending on the presentation of the heat release in the process of burning of the fuel. In the first group heat is generated once an ignition temperature (experimentally determined) is reached in the corresponding cell in the vegetation layer and this heat forms a heat source included in the energy equation (McDonough et. al., 2000; McDonough et. al., 2004; Paz, 2000). This heat source is presented as a function of the heat content of the vegetation particles and the rate of variation of the vegetation mass. Normally, the ignition temperature is assumed to be within 300–400°C (after the moisture in the fuel has been released) and therefore, the value assumed for the amount of heat to be released during the burning process is the value which corresponds to the higher heating value (HHV). The variations in the mass of the fuel result from the thermal decomposition which is in turn dependent on the rate of heating up of the vegetation, as well as on the temperature and the chemical composition of the vegetation layer. Very often variations in the mass are modelled based on the rate of devolatilization of the fuel. Due to the lack of sufficient data for the different types of vegetation involved, the kinetin rate is used with values for the activation energy and pre-exponential factors based on data for coal particles (Paz, 2000; Zhou et al., 2000; De Bruyn Kops et al., 2004).

The second group of models considers the processes of thermal decomposition of the vegetation and the oxidation of volatiles, char and tar. Modelling of chemical processes is used and these involve one to several chemical reactions (Zhou et al., 2000; De Bruyn Kops et al., 2004; Marcelli et al., 2004) and they only provide one very general presentation of the complex phenomena involved in the combustion of the vegetation layer. The right choice of the system of chemical reactions, the rate and the type of the chemical processes, as well as the rate of release of the reagents and their chemical composition, are all highly significant for the amount of heat released in the fire zone and hence, for obtaining the physical picture of the temperature distribution, of the distribution of the other parameters of the gas flow, as well as the characteristics of the fire behaviour.

1.4.4.5. Modelling the mass loss rate of vegetation layer

The rate of conversion of the vegetation into gaseous products maintaining the burning process is not among the characteristics of fire behaviour but it affects to a considerable degree the intensity and rate of spread of the fire. It is a well known fact that reductions in mass of solid fuel are associated with the heating up and the accompanying processes of moisture evaporation, release of volatiles, and formation of tar and solid carbon. The latter three undergo oxidation in the course of the burning process. It is exactly the rate of generation of these products that is expressed by means of mass loss rate. The main factors that affect the reduction of the mass of the vegetation bed in the course of thermal decomposition are the rate of temperature rise and the fuel temperature. The method used for determining mass loss rate is based on the differential thermal analysis (DTA). However, when this method is used the rate of temperature rise is rather limited and therefore, it is possible to obtain more reliable data for the particular characteristic being considered here only when specifically designed laboratory devices are used to study the fire behaviour for intentionally initiated fires.

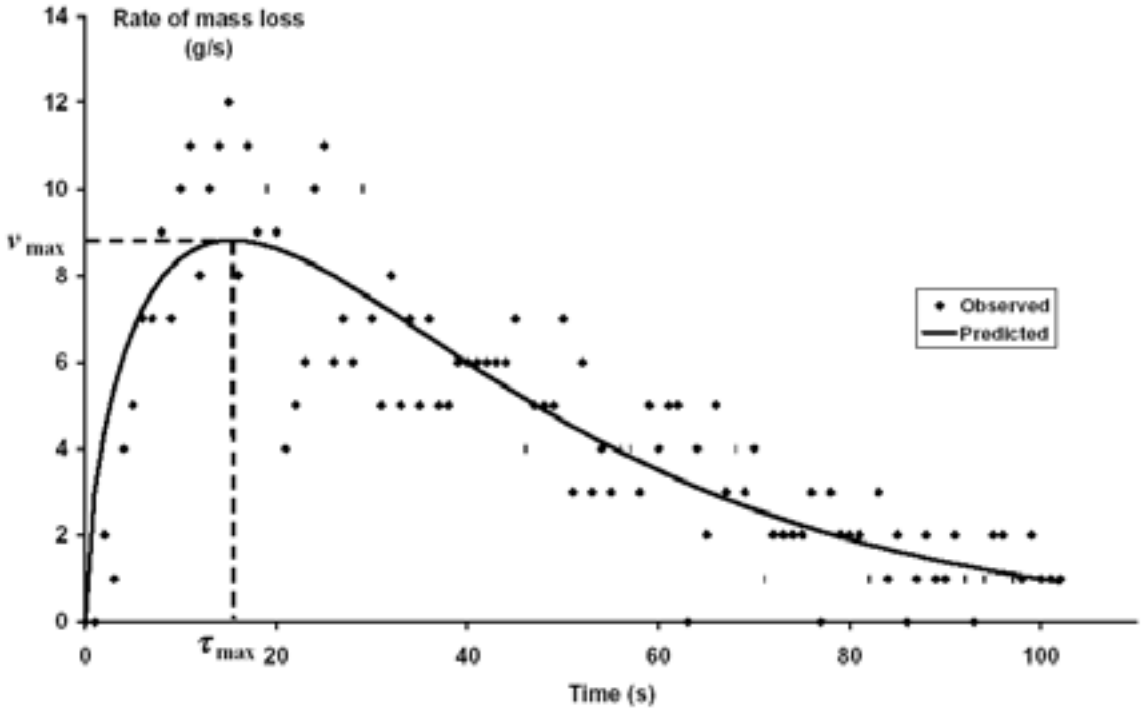


Fig. 1.4 Time evolution of the rate of mass loss (Fuel + PP, D = 0.4 mm, Plate = Yes) (Dupuy et al., 2002)

In their reports Leoni et al., (2002) and Dupuy et al., (2002) describe experimental rigs and present measurement results on *mass loss rate* for pine litter. These experiments were conducted with the purpose of creating models for fuel mass variations throughout the burning process. This data can be useful in the modelling process: fuel moisture evaporation rate, combustion gas emission rate, and also in comparing these results with the results of the numerical modelling of a process of fire spreading in a vegetation bed.

1.5 Thermal Decomposition and Combustion of Vegetation

1.5.1 Thermal Decomposition of Vegetation

What are the changes that occur in vegetation when heat is transferred? In short-term heating of up to 100^{0}C no chemical changes are observed in wood. The moisture content of wood is evaporated. Heating wood up to 125^{0}C completes the process of evaporation of the moisture content. When wood temperature reaches up to 210^{0}C, chemical reactions take place in wood as a result of which a mixture of gases is generated (70% carbon and 30% carbon-based combustion mixtures), along with some volatile compounds (CO, H etc.), thus reducing the mass of wood. If a flame is brought near wood at this temperature it bursts into short flames, i.e. the wood ignites. This temperature is called ignition temperature. Heat generation occurs as a result of the process of oxidation of wood and the reaction is exothermal. At temperatures of 260^{0}C wood combustion is steady-state and the temperature is referred to as flame-burning temperature. As the temperature of wood increases the amount of combustion gases generated increases and the generation of non-combustion CO_2 reduces. At temperatures of 450^{0}C the process of generation of gases from wood stops, flames disappear and surface combustion of the coke residue (carbon) is initiated, which rises the temperature up to 900^{0}C (Videlov, 1993).

Fuel oxidation can be described from the following simplified reaction:

$$\text{Wood} + \text{air} \Rightarrow \text{water} + \text{carbon dioxide}$$

$$(C_6H_{10}O_5)_n + 6n\ O_2 \Rightarrow 5n\ H_2O + 6n\ CO_2$$

The stages of vegetation oxidation are (Johnson et al. 2001):

- Ignition – wood oxidation occurs in a single point of the wood surface;
- Inflammation – oxidation spreads along the entire surface of wood;
- Combustion – oxidation normally spreads on the external surface of wood.

Wood undergoes the following stages throughout the burning process – evaporation of moisture content, evaporation of volatile compounds, generation of fluid products, combustion of hard coke residue and glare (Byram, 1959a: 64–69).

Wood consists approximately of 50% carbon, 44% oxygen and 5% hydrogen 1by weight (Johnson et al., 2001: 57). 5,9 kg (4,6 m^3) of air is required for the complete burning of 1 kg air-dried wood. The mineral residue of the combustion of wood is 0.5% of its initial mass (Videlov, 1993).

The Drying is energy consuming (exothermic) process and is considered to be finished when the moisture contents of the fuel are evaporated. The moisture contents, achieved by proximate analysis are definitive for the description of the entire process. The heat-up of the fuel is evaluated as the rate of the change of its temperature, i.e. [K/s]. At low drying rates (usually 10–10^3 K/s) the water contents are diffusing to the fuel surface and evaporate, as well as released through the pores of the sample. It worth saying that the structure (ash lattice) of the fuel sample is definitive for this process. At these levels of heat exchange the temperature of the sample could be considered constant and homogeneous. At high heating rates (up to 10^5–10^6 K/s) the moisture contents are released rather intensive and even could evaporate inside the pores of the fuel particle (no homogeneous temperature distribution in the fuel particle volume is observed), thus increasing internal pressure and even burst the solid matter. However this rarely happens, so one could assume more convenient (especially for modelling purposes) process, which occurs at low heating rates and resulting homogeneous temperature distribution. At drying regime the temperature of the fuel sample is relatively low (up to 100°C at atmospheric pressure) and no intensive thermo-destruction of the hydrocarbons proceeded. The energy, consumed for water evaporation in case of forest fires is energy (predominantly supplied by radiation) released during combustion of the biomass fuel and rules as extinction factor for the burning process.

Devolatilization. When the drying process has finished the biomass fuel consists only of combustible matter and ash (mineral matter). The combustible matter consists of volatiles, tar and solid carbon residue. The volatile gases are products of thermal degradation of the combustible matter. Due to external heat supplied to the fuel the chemical chains of the complex hydrocarbons are broken and light organic matter – volatiles, is produced as well as tar. There is deep commitment between the heat-up rate of the fuel sample and yield of volatiles – as the heating rate is increased the released volatiles quantity is higher and respectively the tar yield is relatively lower. The thermal degradation is basically exothermic process and three staged of this process could be observed (Johnson et al., 2001). The energy, consumed for light gases devolatilization is called latent energy of devolatilization. Some authors (Kjaldman, 2000) ignore this energy, when come to build model for the devolatilization process, but principally this heat quantity is "hidden" .into the latent heat for water content evaporation.

Experimental observations as well as researchers data show that at thermal degradation (pyrolysis process) around 80% of the mass is released through volatile gases (Richard et al., 2002). This again confirms that the vegetation material could be treated as gas releasing surface in close mass and energy interaction with the homogeneous phase. The remaining solid phase release tar and char residue. The released tar is secondary thermal degradation based step and is converted into gas phase by oxidation. The char residue is consumed by surface reaction, which is diffusion limited, i.e. the diffusion of the oxygen to the reacting surface is the limiting factor and thus the reaction determining one. The experimental investigations of the combustion process of wood based biomass show that the volatile gases are released in the form of non-oxidized chemical species in the gaseous phase, primarily as CH_4, CO, H_2, O_2, C_xH_y and these components undergo chemical reaction in the following mixing process if appropriate conditions occur (Morf et al., 2002).

The pyrolysis temperatures for the three main constituents of the combustible matter of vegetation vary as follows: hemicelluloses at 200–260 °C, cellulose at 240–350 °C and lignin at 280-500 °C. The extended period of contact between the primary products allows their re-polymerization, cracking and/or cross-linking to produce char. Consequently at high heating rates the yields of char decreases (20% of original cellulose weight at about 300 [°C/s], compared to about 2% at 1500 [°C/s]). With an appropriate heating rate thin samples of cellulose (as pine litter can be considered) can be completely volatilized with no production of residual char. In principal besides of the heating rate, char formation is a function of particle size and the moisture contents as well as the mineral matter properties and ash contents. The experiments show that with increasing amount of inorganic contents the char yield is increasing. Thus for relatively big fuel particles (or agglomerations of the pine litter matter) and increased moisture content and at slow heating rates the result is high char formation and relatively low combustible matter conversion.

The three-step pyrolysis process is described in the following diagram.

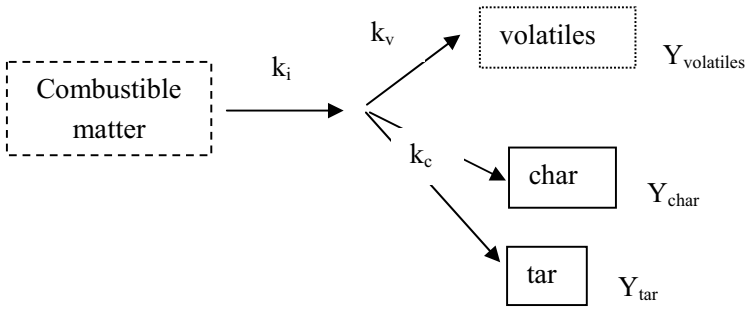


Fig. 1.5 Three-step reaction scheme for the pyrolysis process

$$Y_{volatiles} + Y_{char} + Y_{tar} = 1 \tag{1.16}$$

where $Y_{volatiles}$, Y_{char} and Y_{tar} are mass fractions of the volatiles ,char and tar consequantly, [-].

The consumption rates are Arrhenius type expressions as follows:

production rate of the volatile gases k_v

$$k_v = 3.17x10^{14} \exp\left(-\frac{47300}{Ru.T}\right), [1/s]; \tag{1.17}$$

production rate of the char + tar k_c

$$k_c = 1.32x10^{10} \exp\left(-\frac{36600}{Ru.T}\right), [1/s]; \quad (1.18)$$

In equations (1.17) and (1.18) R_u is universal gas constant (Ru=8314 [J/(kmol.K)]) and T is the absolute gas temperature, [K].

The presented values for the activation energy and the pre-exponential factor given here are corrected and adjusted as the values are specific for each reaction and are function of the environment conditions of the process (Peters et al., 2002; Richard et al., 2002; Brush et al., 2003).

1.5.2 Combustion Process

1.5.2.1. Turbulent combustion models

Principally the problem of the mathematical modelling of turbulent-combustion processes is reduced to the task of modelling the interaction between the turbulence and the chemical reactions. The combustion process in forest fires occur at conditions of continuous changes in the temperature, concentration of chemical components, velocity and chemical state of the reacting species. Under these conditions the process can be presented mathematically by formulating a complex system of non-linear differential equations, which covers following areas: flow approximation, turbulence, chemistry, heat transfer (radiation, convection and conduction), thermochemical data for the species involved, problem geometry and initial and boundary conditions, and application of complex mathematical model to involve all these models.

The determination of the chemical reaction rate is the basic problem in combustion processes modelling. There is a large variety of models developed for turbulent combustion modelling. There are more then 100 models known and published in the literature. Their description is a huge task, but the models most widely used for practical predictions can be grouped in several approaches and classified according their development, application and improvement. Some of these models will only be mentioned in the following section and the emphasis will be on applied combustion model – eddy dissipation model (EDM).

Turbulent combustion models, based on the "flamelet theory". These methods assume that the turbulent reacting flows consist of an ensemble of reaction-diffusion layers that are continuously displaced and stretched within the turbulent medium. The structure of the flamelets can be approximated by employing the flame sheet model or by assuming equilibrium or partial equilibrium. Several "flamelet" based models for turbulent combustion are developed. Some of them are: *Flamelet Surface Density Models*, *Algebraic model of Bray-Libby-Moss*, *Model using transport equation for the mean flame surface*, etc.

P*robability density function models* (PDF). Taking into account the stochastic character of the turbulence it is logical to use the Probability Theory for mathematical describing of the turbulent flow field. Further the method is extended in deriving a transport equation for a joint (for the velocity components and for the scalars) probability density function. Thus becomes possible to define the velocity and the scalar components together. Therefore the joint PDF (JPDF) approach is widely used in turbulent combustion modelling. The idea is that the realistic chemistry, which includes a detailed chemistry, can be presented clearly, without any assumptions for the flame structure. However, the effects from the molecular processes and the pressure fluctuations gradient appear in the equation as conditional expectation, which has to be modelled. Obviously, the transport equation includes many unknown terms. The solution of the JPDF equation increases drastically the CPU time, thus leading to problems with the numerical implementation.

The *turbulent models based on the eddy dissipation approach*s are widely used in combustion modelling society because of their capacity to represent the combustion physics, computationally not so expensive as well as achieved results are qualitatively comparable and close to the experimental data.

Eddy Break Up Model (EBU). This model was presented by Spalding and widely used in the 1970s. The idea of the EBU model is based on the following assumptions: combustion proceeds as an infinitely fast reaction; the chemical reaction rate R_t is proportional to the rate of dissipation (ε/κ) of the individual eddies; the whole process is presented as a single, irreversible one-step reaction:

$$[1\text{kg of fuel}] + [\nu_{Fuel}\ \text{kg of oxidizer}] \rightarrow [(\nu_{Fuel} + 1)\text{kg of products}] \tag{1.19}$$

These assumptions lead to the following mathematical expression for the reaction rate R_{EBU}:

$$R_{EBU} = C_{EBU}\rho\frac{\varepsilon}{\kappa}\sqrt{\overline{Y'^2_{fuel}}}\ ,\ [\text{kg}/(\text{m}^3\text{s})] \tag{1.20}$$

where C_{EBU} is model constant, ν_{Fuel} – stoichiometric coefficient (amount of oxygen ,required to oxidize 1kg of fuel at stoichiometric condition), κ – turbulent kinetic energy , $[m^2/s^2]$, ε – dissipation rate of the turbulent kinetic energy, $[m^2/s^3]$, ρ – gas density, $[kg/m^3]$.

This equation expresses ideally the fact that the local chemical reaction rate depends on the gas mixture fluctuating components Y`. However, in practice this leads to a number of complications related to defining almost unpredictable variables such as fluctuations. The application of the EBU model is also mostly limited to modelling only pre-mixed combustion [PhD thesis Dobrin].

1.5.2.2. Eddy Dissipation Combustion Model (EDM)

This model is proposed by Magnussen and Hejertager (1977). The model develops the conception of eddy dissipation and overcomes successfully some problems related to EBU. In this model the chemical reaction rate is presented by the mean mass fraction values of the reacting species instead of their fluctuations – actually this is the main advantage of EDM compared to EBU. The main factor influencing the rate of infinitely fast chemical reactions is the diffusion of species. The chemical reaction itself takes place when the reagents have mixed up to the molecular level at high temperature. The chemical reaction rate is determined by the mixing rate, i.e. by the rate of dissipation of eddies. The fuel and oxidant appear as fluctuating intermittent quantities so that a correlation is possible to exist between the fluctuations of the chemical components and their mean values ($\overline{Y} \approx \sqrt{\overline{Y'^2}}$). Thus the reaction rate REDM can be expressed by the eddy decay rate and average mass fraction of the reacting elements.

Because of its simplicity and testified applicability it is one of the most popular concepts for modelling local reaction rates in practical turbulent combustion systems. This model has the ability to handle premixed, partially premixed and non-premixed combustion with sufficient accuracy.

1.5.2.3. Methane oxidation model

Methane oxidation will be reviewed in order to present developed models for chemical reactions of CH4 as representative for hydrocarbons. This oxidation model is used as basis for development set of chemical reaction that is applicable to complex problems, such as biomass and vegetation combustion process.

The process of methane oxidation is well known and therefore several mechanisms for the kinetics can be found in the literature. These mechanisms can be classified as:

- *Full mechanism* describes the interaction between hydrocarbons and the so called nitrogen chemistry. It consists of 225 elementary reactions and 48 participating species. Detailed description of each of these reactions is not necessary when practical engineering problems are considered, considering that their numerical investigation is limited by the computer possibilities.
- *Skeletal mechanism* is obtained from the full mechanism after analysing the rate of generation and consumption and the dependence of the solution to the boundary conditions. Actually the skeletal mechanism represents a compromise and balance between complexity, accuracy and applicability of the model.
- *The reduced mechanism* represents the methane oxidation under ideally stirred reactor and therefore it is of special interest for the current investigation.

The chemical reaction included in four steps reduced mechanism are:

$$CH_4 + 2H + H_2O \rightarrow CO + 4H_2 \quad (1.21a)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (1.21b)$$

$$2H + M \rightarrow H + H + M \quad (1.21c)$$

$$O_2 + 3H_2 \rightarrow 2H + 4H_2O \quad (1.21d)$$

This mechanism is more detailed than one and two step reaction mechanism, but actually in some cases makes the numerical modelling unstable and slow converging, the results are close to the less complicated and more computationally stable two step reaction model without paying the efforts for describing the complex chemistry phenomena.

Two steps reduced mechanism is proposed [Dryer et al.] and it is valid for high temperature oxidation of CH_4 and CO, as follows:

$$CH_4 + 3/2O_2 \xrightarrow{R^{kin}_{CH_4}} CO + 2H_2O \quad (1.22a)$$

$$CO + 1/2O_2 \xrightarrow{R_{CO}^{kin}} CO_2 \tag{1.22b}$$

The numerical simulations based on the two steps mechanism, depicted with equation (1.22a) and (2.22b), show a good approximation of the combustion process. This mechanism can be used for both: initial calculation followed by more detailed calculation of the turbulent combustion and for the complete calculation of the combustion process. Furthermore, the results are quite close to the experimental data and thus reliable applicable in most of the engineering combustion problems.

One step global reaction mechanism. This model is based on the assumption for an infinitely fast reaction where CH_4 converts directly to CO_2 and H_2O vapour without considering intermediate species.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1.23}$$

The use of this mechanism leads to several advantages when engineering problems are considered and therefore it is widely used. However when local flame characteristics are of importance the model does not provide the adequate accuracy. Actually it commonly over predicts the temperature field and thus introduces significant error in the numerical investigation.

1.5.2.4. Modelling of the turbulence-chemical reactions interaction

The inclusion of the kinetics into the calculation is related to the choice of appropriate model for the turbulent combustion. There are several known techniques for coupling the turbulence and the chemical kinetics, based on the Eddy Dissipation Approach.

The smallest rate is the limiting. When the turbulent mixing and the chemical kinetics are considered to happen simultaneously, it is considered that the limiting factor will be the smallest rate, i.e. the time for the reaction is determined by the time needed of the slowest of turbulent mixing or chemical kinetics phenomena. Thus the effective rate will have the following expression

$$R_{effective} = \min(R_{turbulence}, R_{chem.kinetics}), \text{ [kg/(m}^3\text{s)]} \tag{1.24}$$

where $R_{effectivee}$ is effective rate of the chemical reaction in turbulent reacting flow.

The series process approach is appropriate for first order kinetic rates. The reacting species should mix due to turbulence and once they are well mixed the kinetics are considered. To eliminate the initial composition in the well mixed zone, the two processes, mixing and reaction are considered in series and a global rate is defined as follows:

$$\frac{1}{R_{effective}} = \frac{1}{R_{turbulence}} + \frac{1}{R_{chem.kinetics}}, \text{ [kg/(m}^3\text{s)]} \tag{1.25}$$

This approach is testified and gives more realistic results and is widely applied in applications involving combustion modelling. That's why series approach will be used in development the model for forest fires.

1.6 Experimental Data for Fire Behavior Modelling Validation

The fire progression is pointed out as a determinant parameter when evaluating model performance (Miranda et al., 2005; Dupuy, 1997; Valette, 2000). This process is described by the main fire behaviour characteristics – fire front position, rate of fire spread, flame characteristics (length, height and angle). Temperature and velocity distribution are also included as a characteristics of fire progression.

The second group of experimental data that can be used as a determinant parameter for model validation is concentration of pollutants in a given spot also called air quality data. The experimental results from this measurements are utilized by smoke dispersion models as a way of validating the performed simulations (Miranda et al., 2005).

Experimental data presented in this section are mainly derived from laboratory experiments but also from observations over intentionally caused and controlled fires in pine needles litter. The results presented underneath are experimental data for ROS and flame characteristics, and also data for temperature and velocity distribution in and above the vegetation layer for vegetation types occurring in the regions of the Mediterranean countries: Portugal, Spain, France and Italy. This information is used to analyse the influence of various factors and also for the assessment of the variations of quantitative characteristics determining fire behaviour, as well as in the process of preparation and planning of experimental work involved in determining these characteristics. It is also useful for the theoretical modelling of quality based on the formation of various submodels and also as validation data for the results derived from numerical experiments. No data for experimental fires in a bed of vegetation originating in Greece was found in the course of the research study carried out in available publications on this issue.

The presented results are mainly for a vegetation bed comprising *Pinus pinaster* pine needles.

1.6.1 Rate of Fire Spread and Flame Charakteristics

Simeoni (Corsica – France 2002) describes an experiment conducted in a wind tunnel under various wind velocities (0–3 m/s), slopes of terrain (up to 30°) and 10% fuel bed moisture content. Derived data is presented with no provision made for considering the values for fire behaviour characteristics, and only taking into account the location of the fire front in a given moment after the start of the fire. In the particular experiment the temperature was measured at 3 cm above the fuel bed. The maximum measured temperature (as indicated on the plots) was about 950°C.

According to data presented by Zhou (Portugal 2000), for wind velocities of 0.8 m/s ROS = 0.63 m/min, and for wind velocity of 1.8 m/s ROS = 0.84 m/min. The presented experimental results were obtained from the burning of pine needles *Pinus canariensis* in crosswind conditions. The vegetation fuel bed was 5 cm high. The characteristics of *Pinus canariensis* are: density – 400 kg/m^3; fuel load – 0.55 kg/m^2; surface area to volume ratio – 5600 m^{-1}; cellulosic volatiles – 64.8% and initial moisture content – 0%.

Mendes-Lopes (Portugal 1998) reports on the results obtained in several sets of experiments, which where put forward at different scales, from field to small laboratory rig experiments. A bed of *Pinus pinaster* needles is burned under controlled conditions (wind speed and direction, terrain slope, and fuel moisture content). ROS and geometrical characteristics of the flame are obtained from video records. Results show that ROS increases steeply with wind speed for wind-driven fires but does not depend on wind speed for back-wind propagation. ROS increases slightly with slope for up-hill propagation, and is not slope dependent for down-hill cases. ROS decreases when fuel moisture content increases. Flame angle and flame height are also dependent on wind velocity, terrain slope, and fuel moisture content (Mendes-Lopes et al., 1998).

The fuel bed consists of a layer of *Pinus pinaster* needles. It tries to reproduce a typical L layer found in Portuguese stands, with a load of approximately 0.500 kg/m^2 on dry basis. The conditioned pine needles are scattered uniformly in the tray with a load of approximately 0.500 kg/m^2 on dry basis, and a fuel bed of roughly 3 to 4 cm depth.

The parameters of the experiments are (Mendes-Lopes et al., 1998):

- Wind velocity: -3, -2, -1, 0, 1, 2, 3 m/s;
- Terrain slope: 0^o, 5^o, 10^o, 15^o;
- Slope orientation: up-slope, down-slope;
- Fuel moisture content: (10±1)%, (18±1)%.

ROS increases with the wind velocity at an increasing rate. The effect of slope further enhances this increase. Values range from 0.20–0.25 cm/s for no-wind propagation up to 4.7–7.3 cm/s for 3 m/s wind. For no wind situation, flame height varies between 25 and 35 cm with no apparent correlation with terrain slope. For back-wind flames a small increase of wind speed from zero originates a deep decrease in flame height to about 10 cm; further increase in wind speed does not cause any changes to flame height. A different behaviour can be observed for wind-driven flames. Flame height steeply increases initially, reaches a maximum of about 45 cm for wind speed of, say, 1.5 m/s, and then decreases (Mendes-Lopes et al., 1998).

Presented in Mendes-Lopes (2003) are some additional results to the study published in Mendes-Lopes (1998) and some statistical data processing has been carried out using an analysis of variance (ANOVA).

Viegas (1998) present results from experiments involving the determination of rate of spread and flame characteristics (height and length) for various values of surface load, fuel bed depth, fuel bed porosity and fuel moisture for *Pinus pinaster* pine needles. The wind velocity and slope of experimental table surface are of zero value. The results illustrate the fact that for vegetation bed moisture content values higher than 65% the rate of spread of the fire is equal to zero – it is not possible to maintain the fire in such conditions and it goes out. As moisture content is reduced the ROS increases and this increase is significant in a fire occurring in a vegetation bed with less than 25% moisture content. According to this publication source the maximum values for ROS are 0.4–0.5 cm/s for moisture content of 5%. The fitted curves to presented experimental data are third order polynomials. The relation between ROS and surface load is linear and the rate of spread of the fire increases as the mass of the vegetation bed is increased. The presented results are approximately between 0.1 cm/s for 0.5 kg/m^2 and 0.25 cm/s for 1.5 kg/m^2. The length of the flame is presented as a function of recorded values for ROS (0.1–0.4 cm/s) and it changes in a linear manner within a range of between 2 and 7–8 times the depth of the vegetation bed.

The literature survey carried out shows that the basic conditions which influence fire behaviour to the largest extent are wind velocity, slope of terrain and fuel moisture content. It is possible to provide a quantitative assessment, presented analytically, of the influence of these parameters over fire behaviour characteristics based on a statistical model developed using a regression analysis of experimental data and selecting a suitable analytical presentation for a model equation. In his study Fernandes (Portugal 2002) establish quantitative relationships between important fire behaviour descriptors and its environment that are applicable to low-to-moderately intense fires in maritime pine (*Pinus pinaster*) stands. The experimental burning program was conducted in six study sites within an elevation range of 450–970 m. From the statistical analysis of results Fernandes (2002) derived the following equation for ROS applicable to pine litter:

$$ROS = 0.603U^{0.868} \exp(-0.035M_{sd} + 0.058S), \tag{1.26}$$

where U – wind velocity, km/h;
M_{sd} – moisture content of the surface dead fuel, %;
S – slope, %.

Equation (2.26) provides a model for the effect of wind using the power law function, and the effects of the slope of terrain and vegetation bed moisture content are modelled based on an exponential function.

It should be noted that, although the general behaviour observed is consistent and somehow repeatable, there is an appreciable amount of data scattering that makes it difficult for point-to-point or even case-to-case comparison with numerical simulations.

Fig. 1.6 illustrates a comparative plot presenting the results obtained for ROS for pine needles fuel bed provided by abovementioned sources.

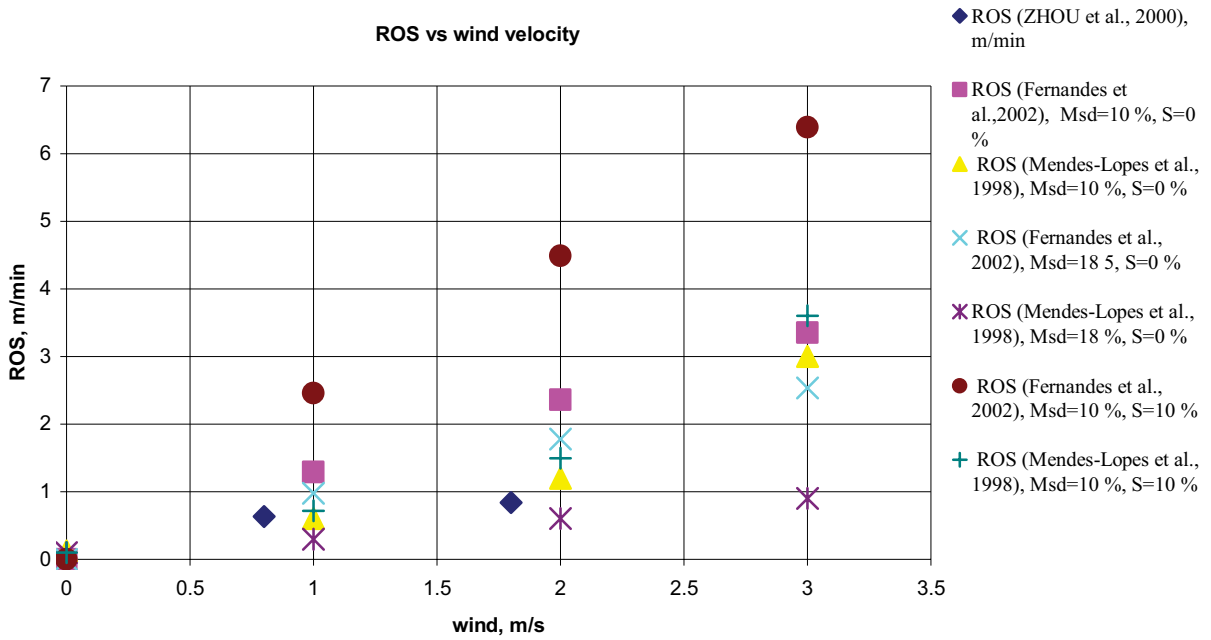


Fig. 1.6 Data for ROS variation by various conditions – wind velocity, slope of the terrain and moisture content

Figures 1.7 through 1.13 provide a graphical illustration of experimental results obtained by Mendes-Lopes (1998), whose report provides the largest amount of data on fire behaviour characteristics.

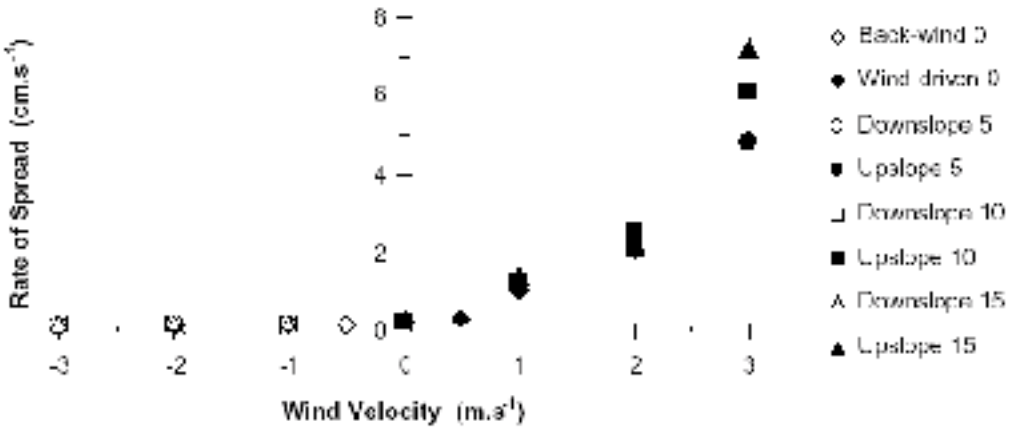


Fig 1.7 Influence of wind velocity on rate of spread, fuel moisture content (fmc) 10 % (Mendes-Lopes, 1998)

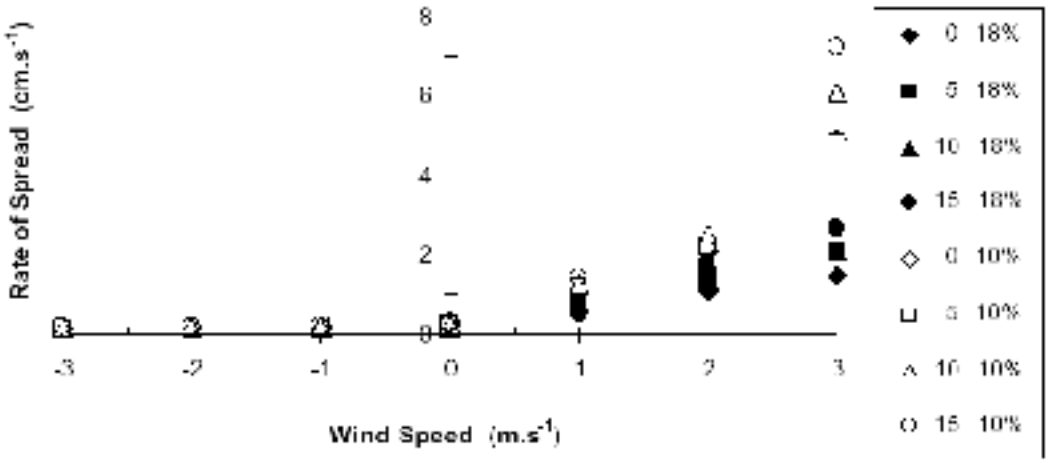


Fig. 1.8 Importance of the fuel moisture content on the influence of wind velocity on the rate of spread (Mendes-Lopes, 1998)

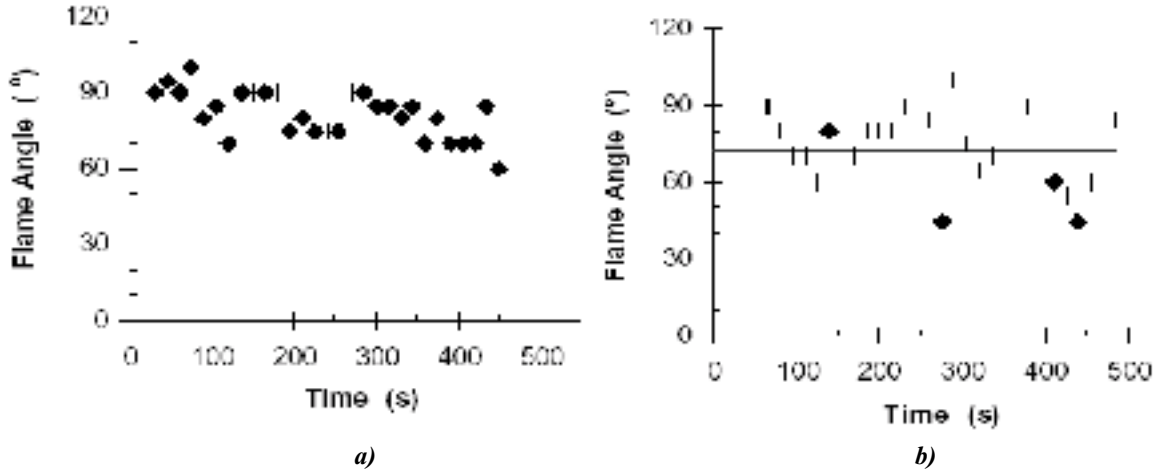


Fig. 1.9 Typical examples of results with different scattering on the discrete values of flame angle measured for two experimental runs: a) low scattering (0 m/s, 0º, 10%); b) high scattering (1 m/s, 0º, 18%)

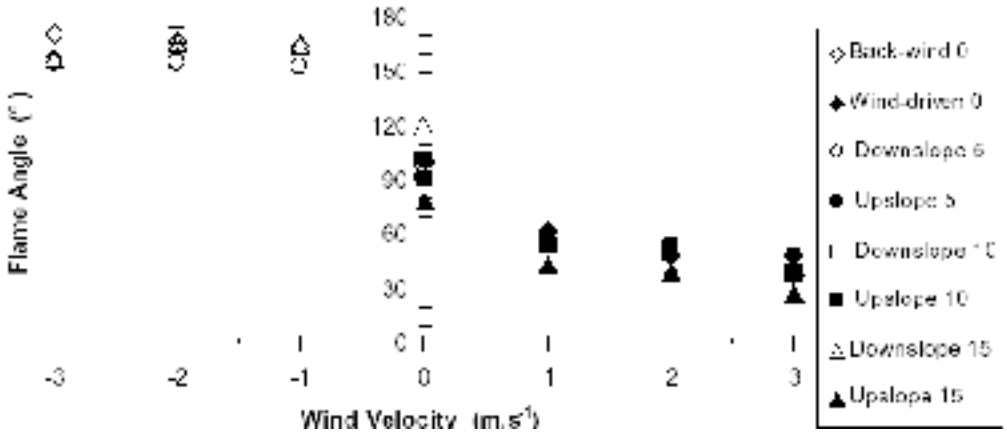


Fig. 1.10 Influence of the wind velocity on flame angle, fmc 10% (Mendes-Lopes, 1998)

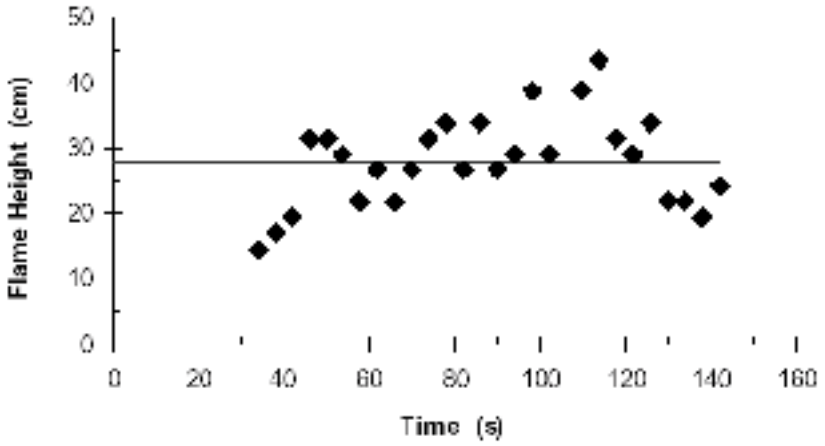


Fig. 1.11 Typical example of variation of flame height with time, wind velocity 3 m/s, slope 0º, fmc 18% (Mendes-Lopes, 1998)

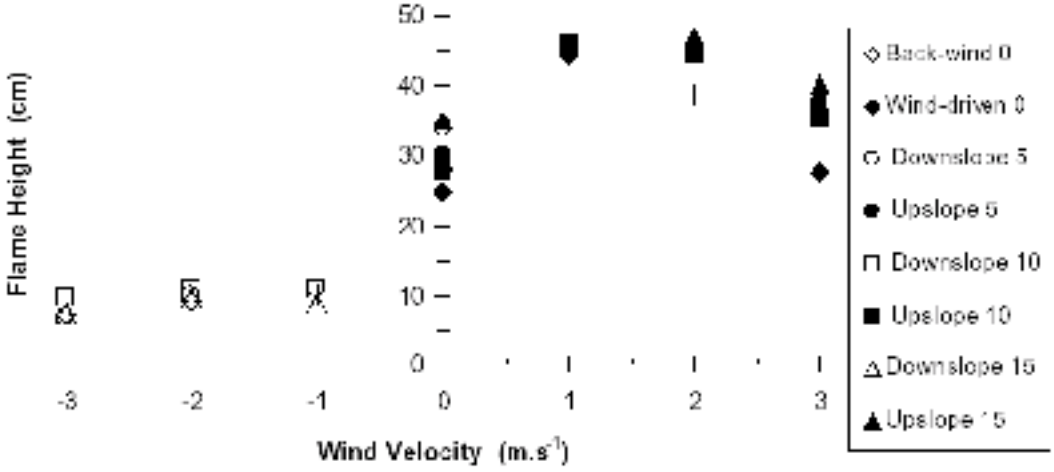


Fig. 1.12 Influence of the wind velocity on flame height, fmc 10% (Mendes-Lopes, 1998)

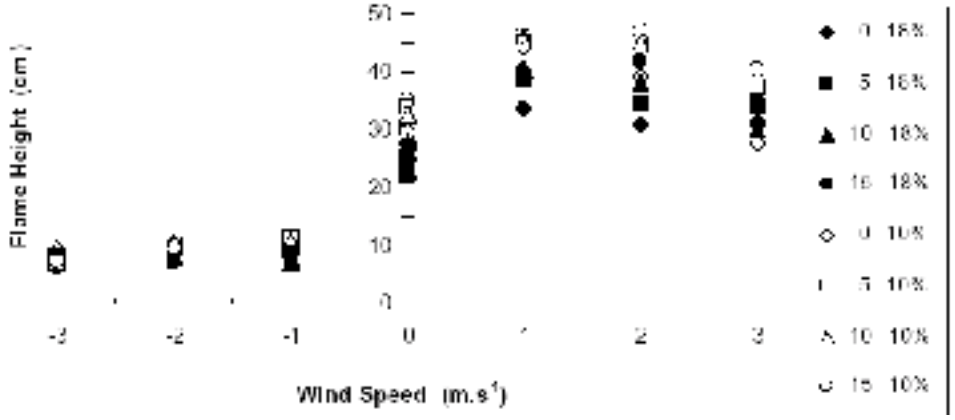


Fig. 1.13 Importance of the fuel moisture content on the influence of wind velocity on flame height (Mendes-Lopes, 1998)

1.6.2 Temperature and Velocity Distribution for and Above Pine Needles Litter

Reports provided by Ventura (1998), Marcelli (2002 and 2004) present measurement results for temperature in and above the fuel bed. The maximum temperature is within the range of 1000–1150ºC with lower values related to wind driven fires (Ventura et al., 1998).

The report provided by Ventura et al., (1998) presents data derived from an experiment that was carried out, and the report of Mendes-Lopes (1998) provides data about the same experiment. These measurements were made in a wind tunnel where wind velocity, fuel moisture and slope were used as parameters to study fire propagation in beds of *Pinus pinaster* needles. The experiments were carried out for 2 different fuel moisture contents (10% and 18%), 4 different slopes (0º, 5º, 10º and 15º) and 7 different wind conditions (from -3 m/s to +3 m/s in steps of 1 m/s). It was very interesting to read the comments provided in the report on the relationship between temperature distribution and flame characteristics.

The results obtained in experimental work by Ventura (1998) are plotted in Figure 1.14., where the maximum temperature reached and the corresponding mean spread rate for all the wind-driven situations are illustrated. It can be seen that the maximum temperature reached for the drier fuel is not dependent on the spread rate (but the rate of spread depends on the temperature). However, this is not the case for the 18% fuel when the spread rate is low, with an initial increase in maximum temperature for an increase in rate of spread, and levelling off for values similar to those of the 10% fuel at high rates of spread. Ventura (1998) considers that as the flame leans further forward, the amount of radiative energy that reaches the virgin fuel increases.

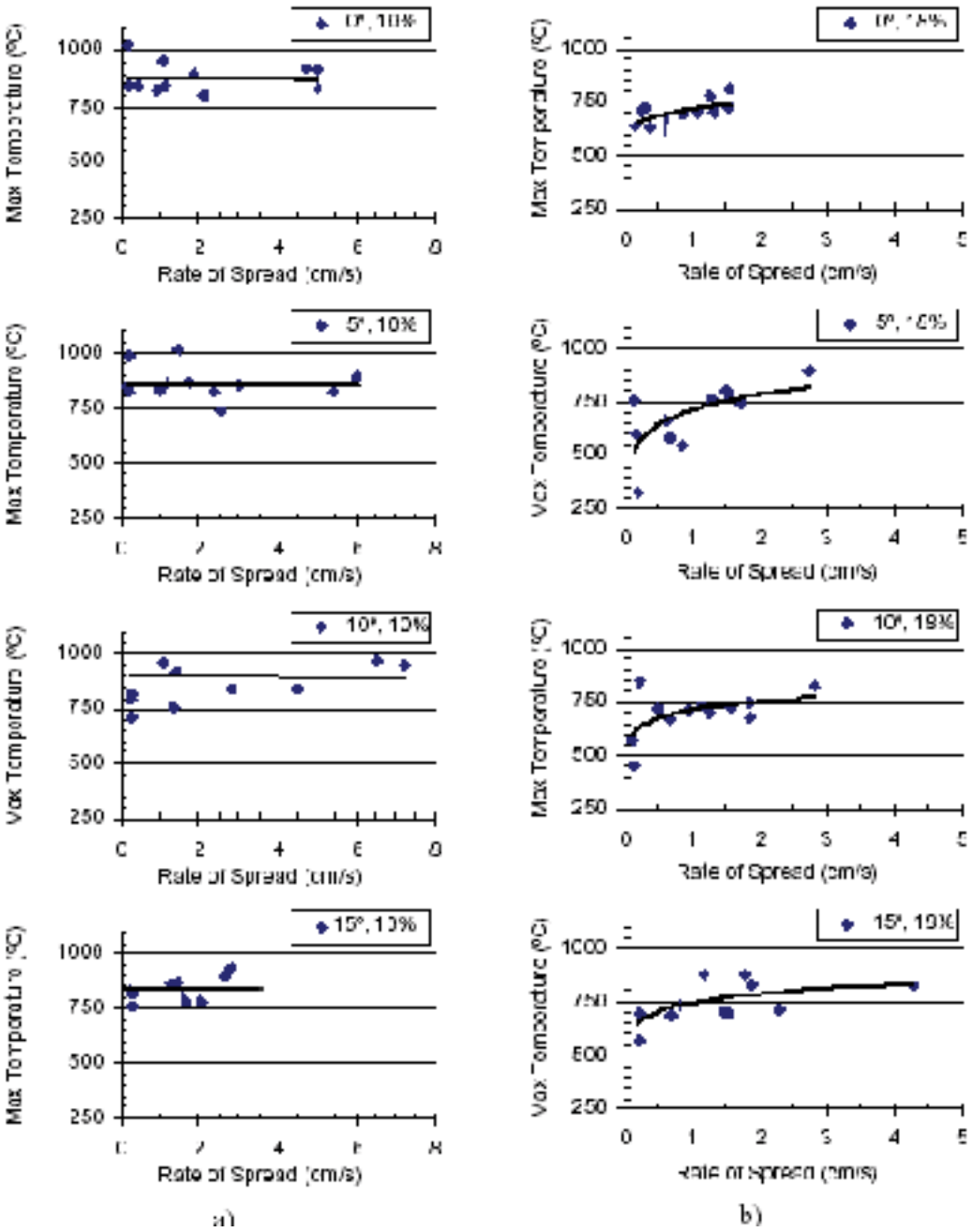


Figure 1.14 Maximum temperature and rate of spread for wind-driven flames: a) fuel moisture content: 10%; b) fuel moisture content: 18%. (Ventura, 1998)

Marcelli (2002 and 2004) reports experiments, which have been carried out in order to compensate the temperature of the flame region for a fire spreading across a pine needle bed and, hence, to measure the upward gas velocity (Table 1.10) in this same region. Experimental fires were conducted in a closed room without any air motion. The properties of the ambient air were measured for each test; the temperature ranged between *25* to *30°C* and the relative humidity varied from *40* to *50%*. The fuel was dead needles of *Pinus pinaster*. Their ratio of area to volume and density is 4550 m^{-1} and 680 kg/m^3, respectively. The depth of fuel was approximately 2.3 cm, giving a bulk density of 21.74 kg/m^3 and a packing ratio of 0.032.

Probe interval [m]	Transit time [s]	Velocity [m/s]	Relative error [%] on estimated velocity
0.04 – 0.06	0.065	0.306	2.04%
0.06 – 0.08	0.027	0.747	7.85%
0.08 – 0.12	0.043	0.926	3.28%
0.12 – 0.16	0.034	1.160	4.40%
0.16 – 0.20	0.030	1.321	6.80%
0.20 – 0.24	0.030	1.342	6.18%
0.24 – 0.28	0.026	1.532	9.34%

Table 1.10 Mean vertical gas velocities (Marcelli et al., 2002)

The experiments used a fuel with a fixed fuel moisture content, thus the needles had to be first dried in an oven at 60°C for 24 hours. They were not completely dehydrated at every experiment since they partially rehydrated during their removal from the oven and the ignition. Thus a sample of needles was taken for every run and loaded to evaluate the moisture content of the fuel before the burning. It was found that the needles were conditioned to a moisture content of 1%–3%.

Some of the results of the experimental work done by Marcelli (2002 and 2004) are plotted in Fig. 1.15 and Fig. 1.16

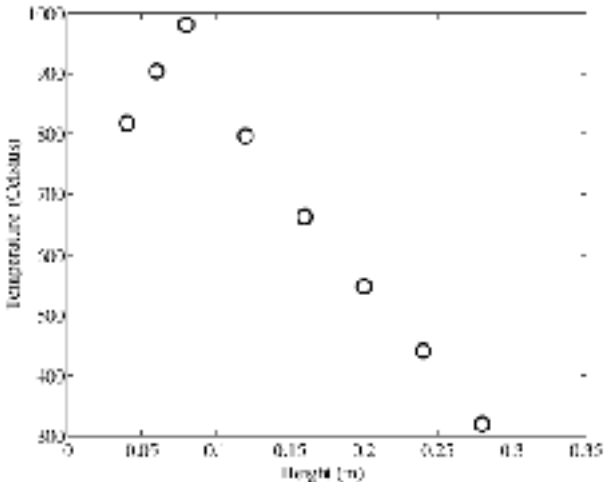


Fig.1.15 Mean temperature profile (Marcelli et al., 2002)

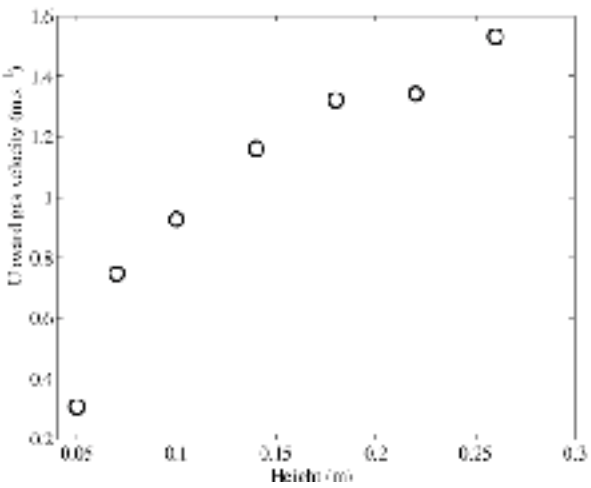


Figure 1.16 Mean gas velocity profile (Marcelli et al., 2002)

Available data for temperature and velocity distribution for and above a pine needle vegetation bed (Ventura, 1998; Marcelli, 2002; Marcelli, 2004) indicate that the maximum value for temperature during a fire could reach 1000°C (Fig. 1.15 and 1.16). This value is measured immediately above the vegetation bed. As the distance (height) increases, the temperature decreases and this corresponds to a reduction in flame intensity. Variations in vertical velocities feature the opposite effect with velocity increasing when height is increased (Fig. 1.11). From the results presented (Table 1.10), it is obvious that the vertical velocity of combustion gases in the vegetation bed is around 0.3 m/sec and rises up to 1.5 m/sec at heights of 0.25 meters.

Bibliography of Items Cited in the Text

1. ALLGÖWER, B., et al., 2002. *Methods for wildland fuel description and modelling: a state of the art* [online]. Available at http://eufirelab.org/D-02-01.pdf [Accessed 5 may 2005].
2. Bachmann A., 2001. Collection of derivatives of the Rothermel model [Online]
3. Barnola L.F., Cedeno A., "Inter-population differences in the essential oils of Pinus caribaea needles", Biochemical Systematics and Ecology 28, 923–931, 2000;
4. Carrega, P., Napoli, A., 1998. A quick protocol of in – the – field measurement for the study of forest and bush fire spread. *3rd International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology, Coimbra (Portugal)*
5. Carvalho E.R., Gurgel Vargas C.A., Carvalho Jr. J.A., "Experimental investigation of smouldering in biomass", Biomass and energy, 22, 283–294, 2002;
6. COHEN, M., 2001. *Wildland fuel particles characterization: database content* [online]. Available at: http://www.eurofirestar.org/D6-03-a1.pdf [Accessed 5 may 2005]
7. Demirbas A., "Combustion characteristics of different biomass fuels", Progress in energy and combustion science, 30, 219-230, 2004;
8. Dimitrakopolous A., "A statistical classification of Mediterranean species based on their flammability components", Int. Journal of Wildland fire, 10, 113–118, 2001;
9. Dimitrakopolous A., "Mediterranean fuel models and potential fire behaviour in Greece", Int. Journal of Wildland fire, 11, 127–130, 2002;
10. Dimitrakopolous A., P. Panov, "Pyric properties of some dominant Mediterranean vegetation species", Int. Journal of Wildland fire, 10, 23–27, 2001;
11. Dormont L., Roquest A., Malosse C., "Cone and foliage volatiles emitted by Pinus cembra and some related conifer species", Phytochemistry, vol. 49, No. 5, pp. 1269–1277, 1998;
12. Dupuy J-L., et al., 2002. Fires from a cylindrical forest fuel burner: combustion dynamics and flame properties.
13. Fagbemi L., Khezami L., Capart R., "Pyrolysis products from different biomasses: application to the thermal cracking of tar", Applied energy, 69, 293–306, 2001;
14. FERNANDES, P., et al., 2002. *Methods for wildland fuel description and modelling: European standarts (intermediate)* [online]. Available at http://eufirelab.org/D-02-03.pdf [Accessed 5 May 2005].
15. Fernandes, P., 2001. Fire spread prediction in shrub fuels in Portugal. *Forest ecology and management,* 144, 67–74.
16. Fernandes, P., Botelho, H., Loureiro, C., 2002. Models for the sustained ignition and behaviour of low-to moderately intense fires in maritime pine stands. *Forest Fire Research & Wildland Fire Safety, Viegas (ed.)*, Millpress, Rotterdam, 1–11.

17. Fletcher D., Haynes B., Christo F., Joseph S., "A CFD based combustion model of an entrained flow biomass gasifier", Applied mathematical modelling, 24, 165–182, 2000;
18. Garzon, V., McDonough J., Saito, K., 2001. Time Dependant Model of Forest Fire Spread in Turbulent Gusting Winds.
19. GILLON, D. et al. 1997. Fast estimation of the calorific values of forest fuels by near-infrared reflectance spectroscopy. Canadian Journal of Forest Research 27: 760–765.
20. Grishin A., 1997. Mathematical modelling of forest fire and a new methods of fighting them. Publishing house of the Tomsk state university (Edited by Frank Albini).
21. Hernando C., 2002. *Physical, chemical and thermal characteristics of the wildland fuel particles. Answer from the partners* [online] Available at http://eufirelab.org/D-02-02A.pdf [Accessed 26 May 2006
22. Jones J.M., Pourkashanian M., Williams A., Hainsworth D., "A comprehensive biomass combustion model", Renewable energy 19, 229–234, 2000;
23. Jonhson J.D., 1984. A rapid technique for estimating total surface area of pine needles Forest science 30(4) 667–673.
24. Johnson, E., Miyanishi, K., 2001. *Forest Fires Behavior and Ecological Effects*. San Diego: Academic Press.
25. Leoni, E., et al., 2002. Mass loss rate modelling for a spreading fire: proposal of an experimental device. *Forest Fire Research & Wildland Fire Safety, Viegas (ed.)*, Millpress, Rotterdam, 1–11.
26. Liodakis S., Bakirtzis D., Dimitrakopoulos A., "Ignition characteristics of forest species in relation to thermal analysis data", Thermochemica Acta, 380, 83–81, 2002;
27. Linn, R., 2002. Studying wildfire behavior using Firetec. *International journal of wildland fire,* 11, 233–246.
28. Marcelli, T., et al., 2002. Gas temperature and velocity measurements in the plume of a spreading fire with double thermocouple probe technique. *Forest Fire Research & Wildland Fire Safety, Viegas (ed.)*, Millpress, Rotterdam, 1–12.
29. Marcelli, T., et al., 2004. Fire spread across pine needle fuel beds: characterisation of temperature and velocity distribution within fire plume. *International journal of wildland fire*, 13, 37–48.
30. Mathieu P., Dubuisson R., "Performance of a biomass gasifier", Energy conversion and management, 43, 1291–1299, 2002.
31. Mendes-Lopes, J., Ventura, J., Amaral, J., 1998. Rate of spread and flame characteristics in a bed of pine needles. *In: III International Confer. on Forest Fire Research 14th Conference on Fire and Forest Meteorology,* Luso*, 16–20 November, 1998*. VOL. I, pp. 497–511.
32. Morvan, D. 2004 Behaviour modelling of wildland fires: Inventory and technical characteristics of wildland fire numerical simulation codes (First version). [online]. Available at http://eufirelab.org/D-03-02.pdf [Accessed 25 November 2006]
33. Nunes-Requera L., Rodriguez Anon J., Castineiras J., "Calorific values and flammability of forest species in Galicia. Coastal and hillside zones", Bioresource Technology, 57, 283–289, 1996;

34. Owen S., Harley P., Guenther A., Hewitt C., "Light dependency of VOC emissions from selected Mediterranean plant species", Atmospheric environment 36, 3147–3159, 2002;
35. Pastor, E., et al., 2003. Mathematical models and calculation systems for the study of wildland fire behavior. *Progres in energy and combustion science*, 29, 139–153.
36. Piccardo M., Pala M., Bonaccurso B., Stella A., Redaelli A., Paola G., Valerio F., "Pinus nigra and Pinus pinaster needles as passive samplers of polycyclic aromatic hydrocarbons", Environmental Pollution 133, 293–301, 2005;
37. Sauvagnargues-Lesage, S., et al., 2001. Experimental validation in Mediterranean shrub fuels of seven wildland fire rate of spread models. *International journal of wildland fire*, 10, 15–22.
38. Simeoni, A., Santoni P., Balbi, J., 2002. A strategy to elaborate forest fire spread models for management tools including a computer time-saving algorithm, *International Journal of Modelling and Simulation*, 22 (4).
39. Ucar G., Balaban M., "Volatile needle extractives of Anatolian black pine varieties: P.nigra subsp. Pallasiana var. pallasiana and var. pyramidata", Biochemical systematics and Ecology 32, 983–992, 2004;
40. Valette J., 1999. EFAISTOS Experiments and simulations for improvement and validation of behaviour models of forest fires its achievements [online].
Available at http://eufirelab.org/e-library/203.pdf [Accessed 20 November 2006
41. Ventura, J, Mendes-Lopes, J., Ripado, L., 1998. Temperature-time curves in fire propagating in beds of pine needles. *III International Confer. on Forest Fire Research 14th Conference on Fire and Forest Meteorology*, I, pp. 699–711.
42. Ventura, J, Mendes-Lopes, J., Santos, C., 2002. Experimental determination of pressure drop through a bed of pine needles. *Forest Fire Research & Wildland Fire Safety, Viegas (ed.)*, Millpress, Rotterdam, 1–11.
43. Viegas D., Pinol J., Viegas M., Ogaya R., "Estimating live fine fuels moisture content using meteorologically-based indexes", Int. Journal of Wildland fire, 10, 223–240, 2001.
44. Zhou X., Pereira, J., 2000. A multidimensional model for simulating vegetation fire spread using a porous media sub-model. *Fire. Mater*. 24, 37–43.