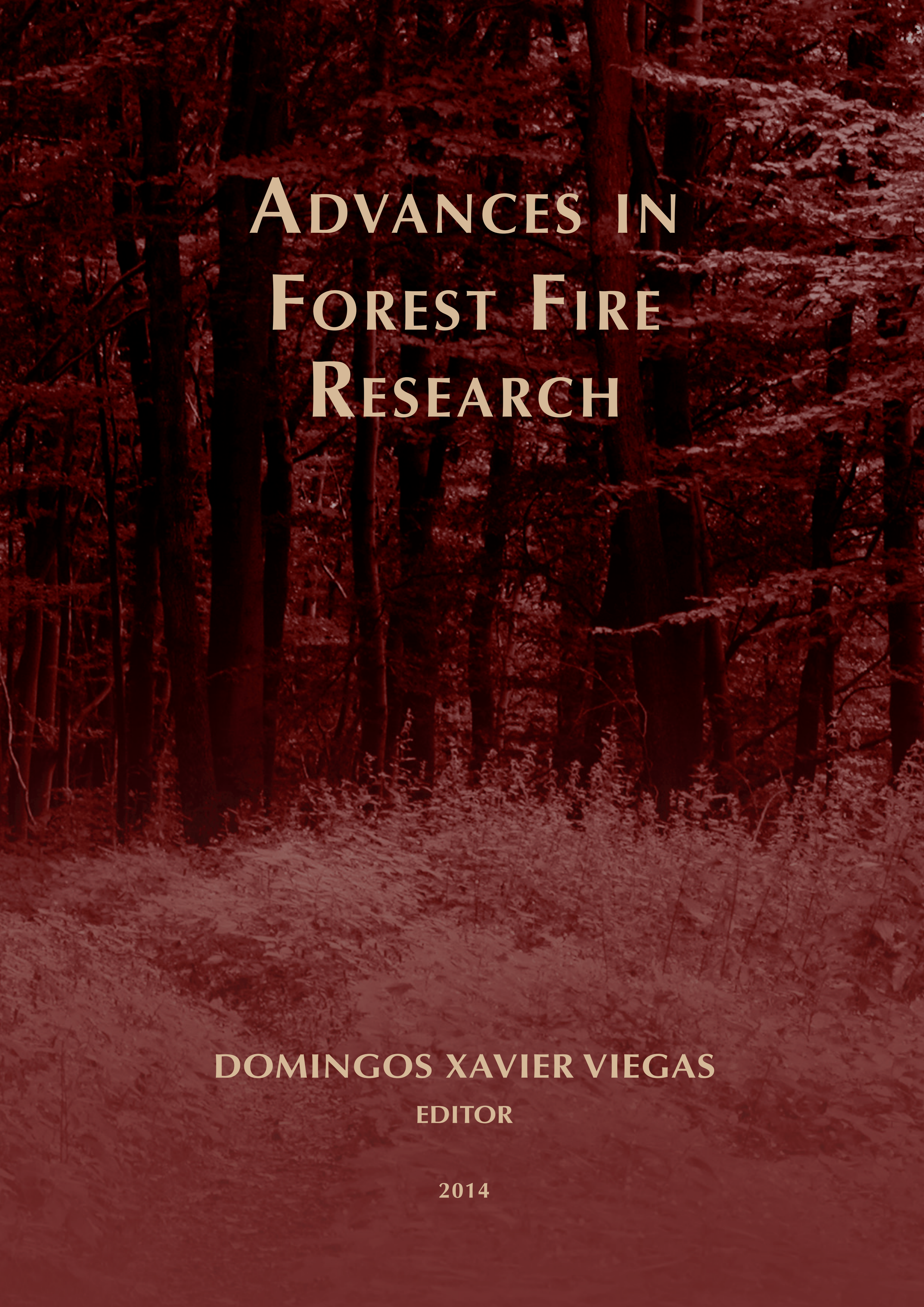

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Experimental and theoretical study of diameter effect on the ignition of cistus twigs

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Abstract

In this work, the effect of the diameter on the ignition of twigs of *Cistus Monspeliensis* was studied experimentally and theoretically. For this, piloted ignition experiments were carried out in a cone calorimeter. In the first part of the study, the location of ignition, the ignition time and the flame residence time were investigated according to the twig diameter. Different modes of ignition were observed. The ignition could be due to: glowing of embers; flaming near the solid; spark of the pilot. The ignition time and the flame residence time increase strongly with the diameter. For small diameters, ignition time can be considered as proportional to the diameter. For high diameters, the ignition time tends to stabilize around a constant value (about 80 s). The second part of the study was devoted to the modelling of the temperature evolution in a twig. A one-dimensional nonhomogeneous heat-conduction problem was considered in finite medium. An optimization was performed to determine the model parameters (ignition temperature, twig emissivity and total heat transfer coefficient). From the expression of temperature in the twig, the ignition time was calculated for the various diameters. The comparison between these values and the experimental data shows a good agreement. Finally, a sensitivity analysis was carried out highlighting the influence of the ignition temperature and of the total heat transfer coefficient on the results.

Keywords: *ignition time, piloted ignition, ignition modelling*

1. Introduction

Over the last decades, modelling of wildfires was increasingly used to provide support decision tools for forest management. Among the models of propagation of forest fires, many use the ignition properties of forest fuel such as the ignition temperature (Rothermel 1972, Koo *et al*. 2005, Santoni *et al*. 2011) and the heat required for ignition (Adou 2010). Some also assume that only small fuel particles contribute to the fire dynamics (Morvan *et al*. 2009). Despite the extensive use of ignition properties, misunderstandings persist even if the first works go back into the 19th century (Hill 1887) and have continued until the present time (Simeoni *et al*. 2012). As pointed out by Babrauskas (2001), literature offers a huge quantity of data and it is difficult to extract relevant values for the ignition properties of forest fuels. Among the studies on ignition, there are little works concerning the diameter influence. Studies realized by Mc Arthur (1962) and Peet (1965) suggested that fuels less than 6 mm diameter contribute most to fire behaviour. For them, the rate of spread of the head fire is directly proportional to the load of fine fuel consumed. In 2001, Burrows (2001) studied the flame residence time and the rate of weight loss for different dimensions of Eucalypt twigs. He concluded that round twigs less than 6 mm in diameter and leaves are the most flammable. Given this state of art, it seems necessary to realise new studies to complete the knowledge about ignition. We propose in the present paper to focus on the effect of the diameter on the piloted ignition of twigs of *Cistus Monspeliensis*. This work is composed of two parts. In the experimental study, the location of ignition, the ignition time and the flame residence time are investigated according to the twig diameter. In the numerical study, an ignition model is proposed. An optimization is used to determine the model parameters (ignition temperature, twig emissivity and total heat transfer coefficient) and a sensitivity analysis is performed to evaluate the influence of these parameters on the numerical results. The aim of this preliminary work is twofold. Firstly, it brings additional data on the ignition of forest fuels. Secondly, it highlights the difficulties encountered during the experiments, leading to new protocols for further study.

2. Materials and Methods

Piloted ignition experiments were carried out in a cone calorimeter (Figure 1a). Twigs of *Cistus Monspeliensis* oven-dried at 60°C during 24 hours were employed as fuel. Table 1 presents the fuel properties. The twigs of *Cistus* were cut to a length of 10 cm and then sorted according to their diameter (Figure 1b). In this study, only diameters between 2 and 17 mm were investigated. The sample holder was an open basket of 10 cm by 10 cm made on stainless steel. It was maintained over an insulating ceramic by a thin metal support. This device reduces the heating process due to the ceramic and metal while allowing air to circulate under the basket. For each experiment, a mass of 15 g of fuel was placed in the basket with a parallel arrangement. A radiant heat flux of 50 kW/m² was imposed on the top of the fuel sample. To ensure that the radiant flux remained the same for all experiments, the heat flux was calibrated using a fluxmeter prior each experiment. The piloted ignition was obtained by using a spark igniter. The time of ignition was determined visually from the appearance of flaming combustion. A visible camera with a rate of 29 frames per second (Lumix ZS19) was placed in front of the cone calorimeter to observe the ignition location. The flame residence time was also recorded. The ambient temperature was 23°C and relative humidity was 40 %. At least 3 repetitions were performed for all the tests.

Figure 1. a) Experimental device b) Twigs of Cistus Monspeliensis used as fuel

Table 1. Fuel properties

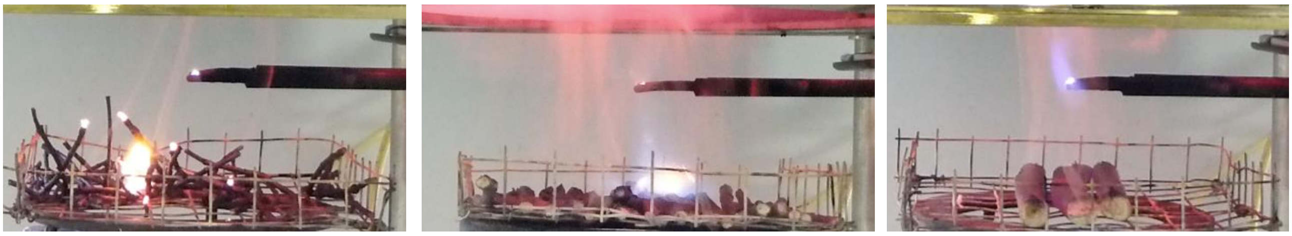
Density ρ (kg/m^3)	Thermal conductivity λ (W/m².K)	Specific heat c_p (J/kg.K)
960	0.42	1834

3. Experimental Results

3.1. Ignition description

After the shutter opening, the twigs of *Cistus* begin to dehydrate (due to the cone heating) and release white smoke. Once the ignition conditions are met, the ignition occurs. Figure 2 shows the first images recorded by the camera at the time of ignition. According to the pictures, the location of ignition seems to vary. The ignition could be due to: glowing of embers (Figure 2a), flaming near the solid (Figure 2b) or spark of the pilot (Figure 2c). However, these observations should be taken with caution.

Because of the recording speed of the camera, it is possible that the ignition actually occurs between two recorded images. In this case, the picture does not represent the ignition location, since the flame spreads. To refine these results, the use of a high-speed camera seems necessary.



a b c

Figure 2. Location of ignition for different experiment

3.2. Ignition time and flame residence time

Figure 3 presents the evolution of the ignition time according to the twig diameter. For diameters under 5 mm, the ignition time increases strongly with the diameter. For a diameter of 2 mm, the mean ignition time corresponds to 25 s whereas for twigs with a diameter of 5 mm, the ignition time reaches 60 s. For these diameters, the evolution of the ignition time can be considered as proportional to the diameter. This is consistent with the ignition theory for thermally thin solids, for which the ignition time t_{ign} is given by the following expression (Quintere 2006):

$$t_{ign} \approx \frac{\rho.c_p.D.(T_{ig} - T_\infty)}{q''} \quad (1)$$

where ρ is density, c_p is the specific heat, D is the diameter, T_{ig} is the ignition temperature, T_∞ is the ambient temperature and q" represents the incident radiative heat flux.

From a diameter of 9 mm, the ignition time tends to stabilize around a constant value (about 79.5 s). This result is in agreement with the ignition theory of thermally thick solids. In this case, the ignition time is indeed independent of the diameter (Quintiere 2006):

$$t_{ign} \approx \frac{\pi.\lambda.\rho.c_p}{4}\left(\frac{T_{ig} - T_\infty}{q''}\right)^2 \quad (2)$$

where λ is the thermal conductivity.

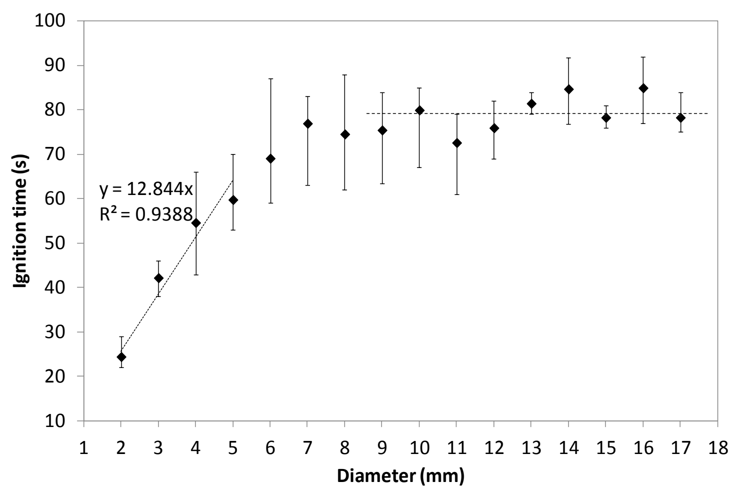


Figure 3. Ignition time according to the twig diameter

Flame residence times for the different diameters are shown on Figure 4. The flame residence time of the twigs increases with the diameter according to the following equation:

$t_r = 13.2 D^{0.96}$ (3)

where t_r is the flame residence time.

This correlation is in agreement with literature (Burrows 2001) even if the increase of the flame residence time with the particle diameter is less significant than that found by Burrows (2001) for eucalypts ($t_r = 0.871 D^{1.875}$). This variation is probably due to the fuel but also to the experimental method.

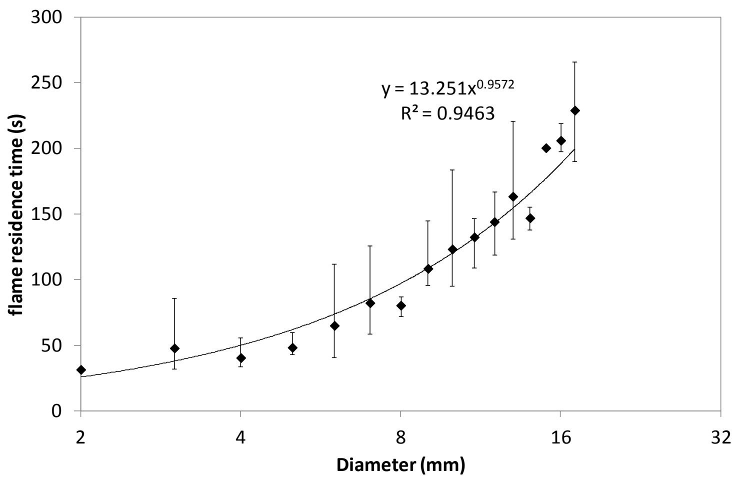


Figure 4. Flame residence time according to a) the twig diameter b) the surface to volume ratio

Given the previous results, it seems that the twigs of C*istus Monspeliensis* can be divided into 3 classes: diameters less than 5 mm, diameters between 5 and 9 mm and diameter above 9 mm. However, these results have to be taken with caution since they depends on our experimental procedure. Indeed, to compare our data with those of Burrows (2001), we kept a same mass for each test. But, this choice has significant consequences. By keeping the same mass, the twig arrangement varies with the twig diameter. For a diameter of 2 mm, the twigs are arranged on three layers on the whole holder surface (Figure 5a). From 4 mm in diameter, twigs are arranged on a single layer (Figure 5b). However, by increasing the diameter, the number of twigs decreases and they cover no longer the entire surface of the holder (Figure 5c). Above 15 mm, there is only one twig (Figure 5d). Therefore, the energy received by the samples is not the same, since it depends on surface exposure that varies from several small twigs at one side to one big twig at the other side. In addition, for small diameter, the set of twigs can be considered as a porous medium. This is no longer true for larger diameter. These variations of twig arrangement certainly affect the ignition and it is difficult to compare the results between the diameters. For a better understanding of the phenomena, rather than using a same mass, a same area exposed to the radiant heat flux appears to be a better alternative.

a b c d

Figure 5– Twig arrangement for a diameter of a) 2 mm b) 4 mm c) 9 mm d) 15 mm

4. Ignition model

4.1. Mathematical formulation

The mathematical model for ignition considered in this article is based on the following assumptions:

- Heat flow in the twigs is one-dimensional, i.e. perpendicular to the exposed surface.
- Chemical effects prior to ignition are negligible, i.e., the delay due to kinetics is neglected.
- Delay due to mixing is neglected.
- Ignition occurs when the surface reaches a given temperature
- The twigs are opaque and the Kirchoff's law is valid for the total absorptivity α, emissivity ε and reflectivity r, i.e., $\alpha=\varepsilon=1-r$
- The value of α, ε and r remain constant between the start of exposure and the ignition.
- The heat losses from the surface are partly radiative and partly convective with a constant convection coefficient h_c. The radiative loss term is linearized using an effective coefficient h_{rad} (Quintiere 2006). A total heat transfer coefficient h including the convective and radiant heat transfers is introduced: $h=h_c+h_{rad}$. This coefficient was considered as constant for all experiments.

Under these assumptions, the ignition problem corresponds to a thermal problem with the following mathematical form:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a}\frac{\partial T}{\partial t} \quad \text{for } 0 < x < D,\ t > 0 \qquad (4a)$$

$$-\lambda \frac{\partial T}{\partial x} = \varepsilon . q'' - h(T - T_\infty) \quad \text{for } x = 0,\ t > 0 \qquad (4b)$$

$$-\lambda \frac{\partial T}{\partial x} = h(T - T_\infty) \quad \text{for } x = D,\ t > 0 \qquad (4c)$$

$$T = T_\infty \quad \text{for } x \geq 0,\ t = 0 \qquad (4d)$$

where T is the temperature, T_∞ is the ambient temperature, a is the thermal diffusivity and σ is the Stefan-Boltzmann constant.

To resolve this one-dimensional nonhomogeneous heat-conduction problem in a finite medium, a variable change $\theta = T - T_\infty$ is used. Then, the problem is decomposed into two simpler problems (Ozisik 1993):

- a steady state problem for $\theta_0(x)$ given as:

$$\frac{\partial^2 \theta_0}{\partial x^2} = 0 \qquad \text{for } 0 < x < D \quad (5a)$$

$$-\lambda \frac{\partial \theta_0}{\partial x} + h\theta_0 = \varepsilon . q'' \qquad \text{for } x = 0 \qquad (5b)$$

$$\lambda \frac{\partial \theta_0}{\partial x} + h\theta_0 = 0 \qquad \text{for } x = D \qquad (5c)$$

- a homogeneous problem for $\theta_1(x,t)$ given by:

$$\frac{\partial^2 \theta_1}{\partial x^2} = \frac{1}{a}\frac{\partial \theta_1}{\partial t} \qquad \text{for } 0 < x < D,\ t > 0 \qquad (6a)$$

$$-\lambda \frac{\partial \theta_1}{\partial x} + h\theta_1 = 0 \qquad \text{for } x = 0,\ \ t > 0 \qquad (6b)$$

$$\lambda \frac{\partial \theta_1}{\partial x} + h\theta_1 = 0 \qquad \text{for } x = D,\ \ t > 0 \qquad (6c)$$

$$\theta_1 = -\theta_0(x) \qquad \text{for } x \geq 0,\ t = 0 \qquad (6d)$$

- Then, the solution of the original problem (5a-d) is determined form:

$$T = T_\infty + \theta_0(x) + \theta_1(x,t) \qquad (7)$$

The solution of the steady-state problem (5a-c) is given as:

$$\theta_0(x) = -\frac{\varepsilon . q''}{2.\lambda + h.D}\left(x - \frac{\lambda}{h} - D \right) \qquad (8)$$

The solution of the homogeneous problem (6a-d) is obtained as:

$$\theta_1(x,t) = -\frac{2}{D}\sum_{m=0}^{\infty} e^{-a.\beta_m^2 t}\, \frac{1}{N(\beta_m)}\, X(\beta_m, x)\int_0^D X(\beta_m, x').\theta_0(x')dx' \qquad (9a)$$

with

$$X(\beta_m, x) = \beta_m . \cos(\beta_m . x) + \frac{h}{\lambda}\sin(\beta_m . x) \qquad (9b)$$

$$\frac{1}{N(\beta_m)} = \frac{2}{D\left(\beta_m^2 + \dfrac{h^2}{\lambda^2}\right) + \dfrac{2.h}{\lambda}} \qquad (9c)$$

$$\tan(\beta_m . D) = \frac{2.\beta_m . h.\lambda}{\beta_m^2 . \lambda^2 - h^2} \qquad (9d)$$

The temperature T(x,t) of the problem (4a-d) is obtained by performing the integration:

$$T(x,t) = T_\infty - \frac{\varepsilon.q''}{2.\lambda + h.D}\left(x - \frac{\lambda}{h} - D\right)$$

$$+ \frac{2.\varepsilon.q''}{2.\lambda + h.D} \sum_{m=0}^{\infty} \frac{e^{-a.\beta_m^2 t}\left[\beta_m.\cos(\beta_m.x) + \frac{h}{\lambda}\sin(\beta_m.x)\right]\left[\frac{h^2 - \lambda^2.\beta_m^2}{h.\lambda.\beta_m}\sin(\beta_m.D) + 2.\cos(\beta_m.D) - 2 - \frac{h.D}{\lambda}\right]}{\beta_m\left[D\left(\beta_m^2 + \frac{h^2}{\lambda^2}\right) + \frac{2.h}{\lambda}\right]} \quad (10)$$

At the surface and at the ignition (x=0 and t=t_{ign}), the ignition temperature is given by:

$$T_{ign} = T_\infty + \frac{\varepsilon.q''}{2.\lambda + h.D}\left(\frac{\lambda}{h} + D + \sum_{m=0}^{\infty} \frac{2.e^{-a.\beta_m^2 t_{ign}}.\left[\frac{h^2 - \lambda^2.\beta_m^2}{h.\lambda.\beta_m}\sin(\beta_m.D) + 2.\cos(\beta_m.D) - 2 - \frac{h.D}{\lambda}\right]}{D\left(\beta_m^2 + \frac{h^2}{\lambda^2}\right) + \frac{2.h}{\lambda}}\right) \quad (11)$$

4.2. Numerical results

The calculation of the ignition time with equation 11 is only possible when the three following parameters are known: the ignition temperature T_{ign}, the twig emissivity ε and the total heat transfer coefficient h. To determine the most suitable set of parameters, we decided to realize an optimization based on the gradient descent method. Several values were tested. For each set of values, the experimental ignition times (t_{ign}^{exp}) were compared to the calculated values (t_{ign}^{model}).

The optimized model parameters correspond to the values for which the sum

$$S = \sum_{i=1}^{N}\left(t_{ign,i}^{exp} - t_{ign,i}^{model}\right)^2 \quad (12)$$

is minimal. Here N is the number of diameters considered.

The set of parameters best describing the experiments is: T_{ign}=491°C, ε=0.982 and h=21.4 W.m².K. For piloted ignition and under radiant heating, the temperature ignition for wood ranges between 296 and 497°C (Babrauskas 2001). This scattering can be explained by the definition used for the ignition, the design of the test apparatus, the specimen conditions and the species of wood. The optimized ignition temperature (T_{ign}=491°C) is therefore in the range of the data found in literature. There is little data concerning the emissivity of forest fuel. Boulet *et al*. (2011) performed experiments using Fourier transform infrared spectrometers to determine the absorption of radiation for different species of forest vegetation. They found values of absorptivity for the vegetation matter between 0.90 and 0.95. The optimized emissivity (ε=0.982) seems therefore to be coherent with these values. In literature, the total heat transfer coefficient is often evaluated by means of the following relationship (Quintiere 2006, Torero and Simeoni 2010):

$$\varepsilon.q''_{ign,crit} = h(T_{ign} - T_\infty) \quad (13)$$

where $q''_{ign,crit}$ is the critical heat flux for ignition

For needles of *Pinus halepensis*, Torero and Simeoni (2010) obtained a value of 22 W/m².K. By using the data given in Quintiere (2006), the total heat transfer coefficient ranges between 34 and 39 W/m².K for wood. As for the other parameters, the value h=21.4 W.m².K is in agreement with literature.

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Figure 6 presents the ignition times obtained with the experiments and with the optimized set of parameters. The comparison between these data shows a good agreement. Both curves follow the same trend. An increase of the ignition time with the diameter appears for low diameters. Then, the curves reach an asymptote for larger diameters.The most significant errors appear for diameters of 2 and 3 mm. As described in section 3.2, for these diameters, the twigs are arranged on several layers. Our modeling considering a thickness D is therefore quite away from the experiments and tends to overestimate the time of ignition. Despite these approximations, the two curves are very close. The mean error is indeed less than 8.3%. However, to ensure the validity of this model, an experimental determination of T_{ign}, h and ε is necessary in order to compare the values found with the optimization and with the experiments.

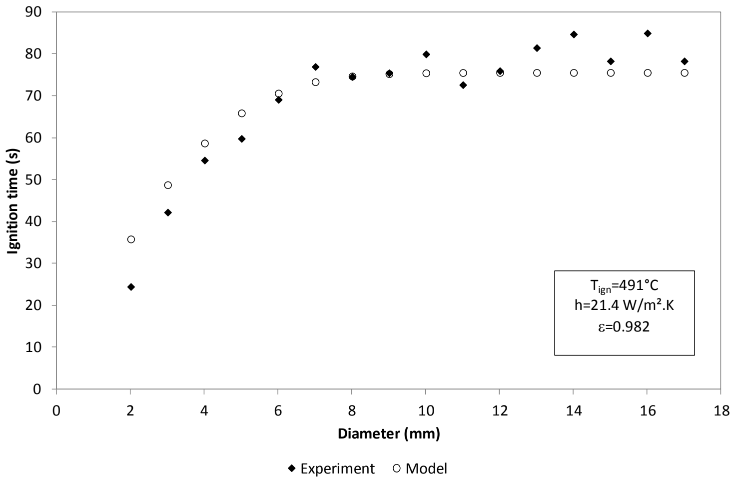

Figure 6– Comparison between the experiment and the numerical simulation

4.3. Sensitivity analysis

To study the effect of the three missing parameters on the ignition time, a sensitivity study was performed. Table 2 shows the three input parameters with their low and high values corresponding to the data found in literature. The interactions between the parameters being unknown, only the interactions between two factors are considered. The factorial design with two levels is therefore built and 2^3 simulations are performed. The software Statgraphics Centurion XVI (StatPoint Technologies) was used to define the numerical design of experiments (Table 3) and to draw the standardized Pareto Chart. The ignition time obtained for high diameters (corresponding to the asymptote of the curve of time ignition according to the diameter) was considered as the output parameter for each case.

Table 2. Variables used for the sensitivity study

Parameter	Low value	High value
T_{ign} (°C)	296	497
ε (-)	0.90	0.95
h (W/m².K)	22	39

Table 3. Numerical design of experiments (DOE)

Test n°	T_{ign} (°C)	ε (-)	h (W/m².K)	Output parameter (Max)
1	497	0.95	22	85.5
2	296	0.95	22	23.7
3	296	0.9	22	26.8

4	497	0.9	22	97.6
5	497	0.9	39	148.8
6	497	0.95	39	126.2
7	296	0.95	39	28.6
8	296	0.9	39	32.7

Figure 7 shows the numerical ignition times according to the diameter for the set of tests. Figure 8 shows the standardized Pareto Chart and the main effects plot. The ignition temperature is therefore the most influent parameter. This is not surprising since this is the parameter which induces the ignition. Increasing the temperature ignition implies an increase of the ignition time. The total heat transfer coefficient affects also the results. By increasing h, the ignition time increases as well. This is due to an increase of the heat losses at the surface. This sensitivity analysis highlights therefore the need to determine accurately the ignition temperature and the total heat transfer coefficient. Specific experiments dedicated to this objective must be considered in the future to obtain these data. This analysis reveals also that the emissivity effect can be neglected in comparison to the effects of ignition temperature and heat transfer coefficient.

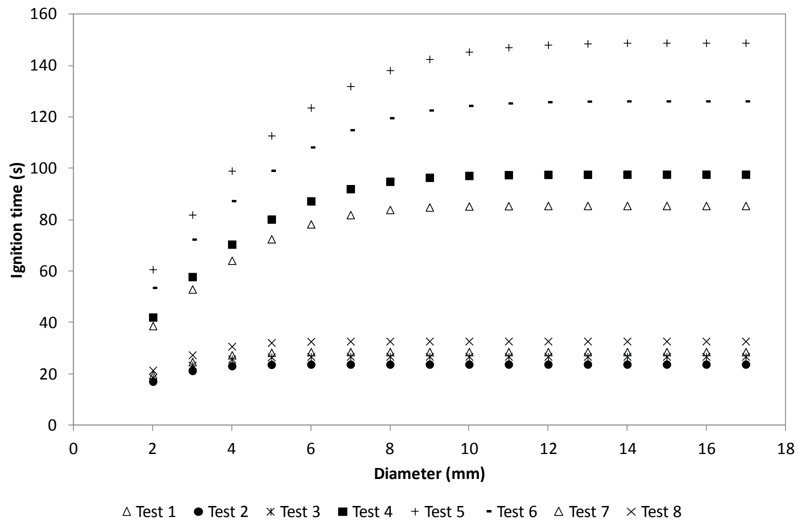

Figure 7– Experimental and numerical time of ignition

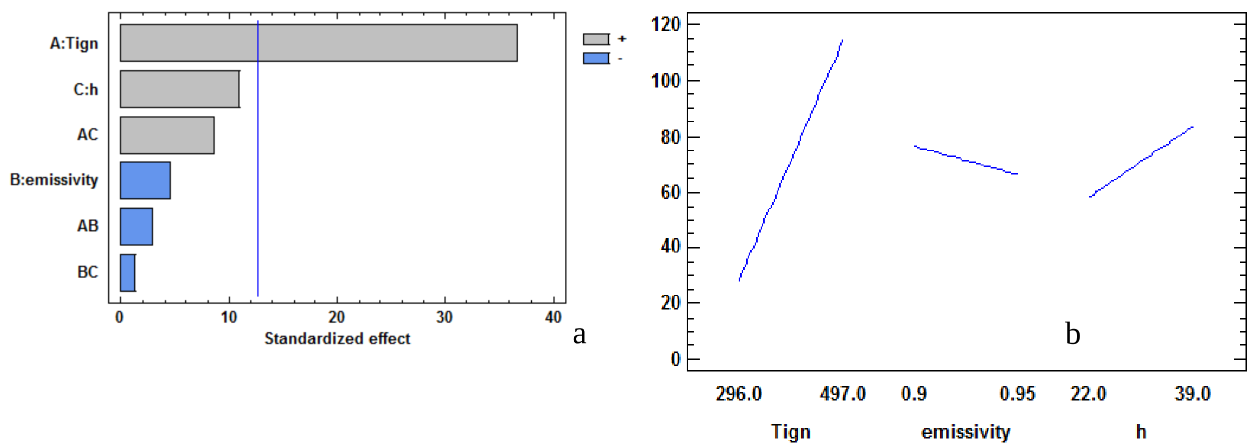

Figure 8– a) Standardized Pareto Chart b) Main effects plot

5. Conclusion

In this article, the first results of the study of diameter effect on the ignition of *Cistus Monspeliensis* twigs are presented. The location of ignition, the ignition time and the flame residence flame in function to diameter were investigated and a model of ignition was proposed. The main results can be summarized as follows:

- The location of ignition seems to vary. The ignition could be due to: glowing of embers, flaming near the solid or spark of the pilot.
- The ignition time increases strongly with the diameter. For small diameters, the evolution of the ignition time can be considered as proportional to the diameter. For high diameters, the ignition time tends to stabilize around a constant value.
- The flame residence time of the twigs increases with the diameter.
- A model based on one-dimensional nonhomogeneous heat-conduction problem in a finite medium allows modeling the ignition time according to the diameter.

In addition, this study also pointed out the necessity to modify the experimental procedure and to perform specific experiments to better understand the phenomena and to obtain the parameters of the ignition model. Based on these observations, a new study will begin soon, for which:

- A high-speed camera will be used
- A same area exposed to the radiant heat flux will be employed rather than a same mass.
- The ignition temperature will be measured for each experiment
- The model of ignition will be tested with the new set of experimental results.

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