Design of a Water Control System Installed in the Tree Trunk in Forest Fire Environment

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Abstract. This article presents a numerical study on the thermal response of a trunk tree, in a forest fire environment, provided with an incorporated water control system. This numerical control system activates the water system when the temperature rises above 60 °C. The numerical model of the trunk tree is based on energy balance integral and differential equations. The virtual trunk tree geometry was developed used adaptive mesh generation. The numerical simulation was made for a fire front propagation at a constant fire spread rate of 0.01 m/s. The temperature distribution in the pine tree trunk, obtained for a flame temperature of 500 °C, will make it possible to identify the areas of the trunk tree that will reach temperatures that will trigger the control system. The results show that the water system will mostly be activated when the fire is on the upstream side of the tree trunk.

Keywords: Fire front · Forest fire · Numerical simulation · Tree thermal response · Adaptive mesh generation

1 Introduction

Portugal has about 39% of its territory occupied by forests [1]. It is one of the countries in Europe with the highest incidence rate of forest fires [2, 3], with more than 20000 occurrences having been recorded for years [4]. This high number of forest fires, some with large extensions of burnt area, have caused significant environmental and socio-economic negative impacts [5]. Therefore, the study of the thermal behavior of forest fires as well as their consequences on the survival of affected trees is justified. The process of direct tree death from fire is the cambium necrosis via heat transfer, by conduction, convection and radiation, to the crown, stem and root tissue [6]. The lethal threshold for trees is reached for temperatures equal or above to 60 °C, although longer exposure at lower temperatures can also cause tissue death [7]. Early detection and combat in the early stages of forest fires is very important to limit its impacts. Early detection and

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combat in the early stages of forest fires is very important to limit its impacts. In this way, automatic fire detection and firefighting systems previously installed in forest areas can make a significant contribution to minimizing burnt areas and the risk to human lives [8].

In this work it is applied a thermal response numerical model to estimate the temperature evolution inside the trunk tree towards a forest fire. This numerical model is founded on the human body geometry, applied on the human thermal response numerical model [9–11]. Knowing the evolution of the temperature inside the tree, it is possible to identify which points will reach the lethal threshold [7]. This situation can then be defined as the moment when the fire in the vicinity of the tree must be extinguished.

The objective of this work, applying an adaptive mesh generation model, is to obtain the evolution of the field temperature in the tree before and after the fire is extinguished. The lethal threshold defines the point at which the fire extinguishing system will operate. The knowledge of these field temperature transient conditions will allow to establish the extent of damage caused to the tree and the response time of the fire extinguishing system. The forest fire is represented by a front fire.

2 Numerical Model

The differential energy equations and the adaptive mesh are used by the numerical model to assess the thermal behavior inside the tree, whose trunk is composed of bark and cambium. The model considers energy balance equations at the boundary between the tree and the surrounding environment as follows:

- Heat conduction with the interior of the tree;
- Heat convection (natural, forced and mixed) between the tree surface and the air environment;
- Radiation between the tree surface and the surrounding surfaces (fire front, fuel bed and sky).

A procedure related to heat exchanges between surfaces of building compartments is used in the radiative exchanges determination. This procedure is applied in the thermal response model of buildings with complex topology and cabins of vehicles. Its application is presented in the studies of Conceição et al. [12–15] and Conceição and Lúcio [16–18]. The temperature distribution inside the tree is evaluated by a finite differences implicit model.

The tree surface contours were developed by a numerical adaptive mesh generation model using the method of finite differences. This mesh generation considers the conversion of a physical space into a computation space done by two Poisson's type elliptic partial differential equations. The adaptive mesh generation used in the present work is shown in Fig. 1. Wind speed, fire front conditions (dimensions, inclination, flame temperature, fire rate spread), tree dimensions, initial distance of the fire front from the tree, lethal threshold and other initial conditions are the input data of this model.

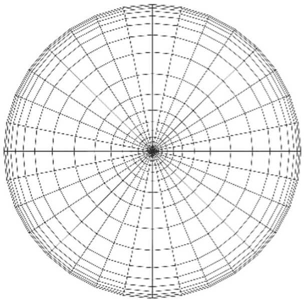

Fig. 1. Adaptive mesh generation used (33 × 20 grid points).

3 Numerical Methodology

The evolution of the field temperature distribution in a tree is obtained as result of the numerical simulation done in this work. The numerical simulation is carried out considering two situations: the fire front propagation occurs without and with the action of the extinguishing system. The numerical extinguishing system consists of a sprinkler located close to the tree that will be activated by a control system operated by a signal received from the temperature sensor of the first point that reaches the lethal threshold. The operating radius of the sprinkler water jet was considered equal to 2 m. Figure 2 shows the progression of the fire front in red, the sprinkler operating radius in yellow and the tree in black. The fire front, within the sprinkler's range of action, is only extinguished when the temperature in one of the points of the tree reaches 60 °C.

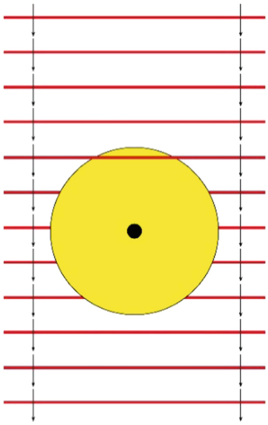

Fig. 2. Operating scheme of the fire extinguishing system. In red, the progression of the fire front; in yellow, the operating radius of the sprinkler; and in black, the tree.

The numerical simulation is characterized by the movement of a fire front at a constant fire spread rate of 0.01 m/s from a distance of 5 m upstream of the tree. The tree is represented by its trunk with a height of 2 m and an external diameter of 0.3 m. The fire front has a tilt angle of 45°, 4 m wide, 2 m high and an average flame temperature of 500 °C. The environmental conditions are characterized by a wind speed of 0.1 m/s, an air temperature of 20 °C and an air relative humidity around the tree of 50%. The temperature distribution was obtained at 33 points (P) equidistant distributed along the external surface (bark) of the tree trunk in a plane located at a height of 2 m and at 20 points (Q) distributed along the radius of the tree trunk, as shown in Fig. 3.

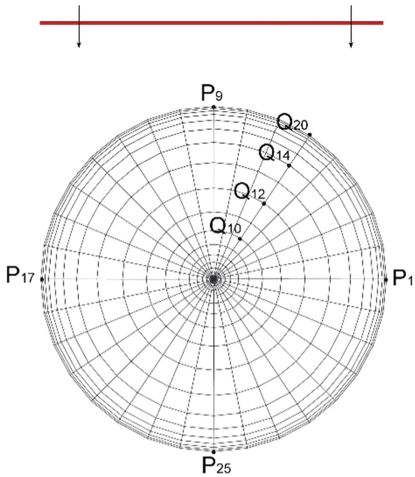

Fig. 3. Location of 33 P-points on the outer surface of the tree trunk and of 20 Q-points inside the tree trunk. The red line represents the progressive fire front.

4 Results and Discussion

The evolution of the field temperature distribution in the surface (points P1 to P33) of the tree trunk is shown for the cases without and with the operation of the fire extinguished system in, respectively, Fig. 4a) and Fig. 4b). In Fig. 4, the red dashed line represents the lethal threshold (TP $\leq$ 60 °C). The evolution of the temperature distribution in the points Q1-Q20 located on the lines of the tree trunk radius is shown in Fig. 5 and Fig. 6 for lines containing, respectively, the points P9 and P25 (please, see Fig. 2 and Fig. 3). The points a) and b) are related, respectively, to the cases without and with the operation of the fire extinguished system. In Fig. 5 and Fig. 6, the red dashed line represents the lethal threshold (TQ $\leq$ 60 °C).

During its progression, the fire front initially affects the side facing upstream rather than the side facing downstream of the tree trunk. Due to the inclination of the fire front, points located on the surface of the upstream side of the tree trunk reach the highest temperatures. The highest temperature, 182.6 °C, is obtained at point P9 after 400 s of simulation time. Point P9 is the first point to reach the value of 60 °C, which happens after 260 s of simulation time, that is, when the top of the fire front is about 1 m from the tree trunk. At this moment the fire extinguishing system starts to operate. Then, it is verified that the temperature at all points of the tree trunk surface evolves below 60 °C (see Fig. 4b)). The fire extinguishing system will operate for approximately 260 s. After the fire front has passed off the tree, its re-establishment will no longer cause problems as the temperatures obtained on the surface of the tree trunk are significantly below 60 °C.

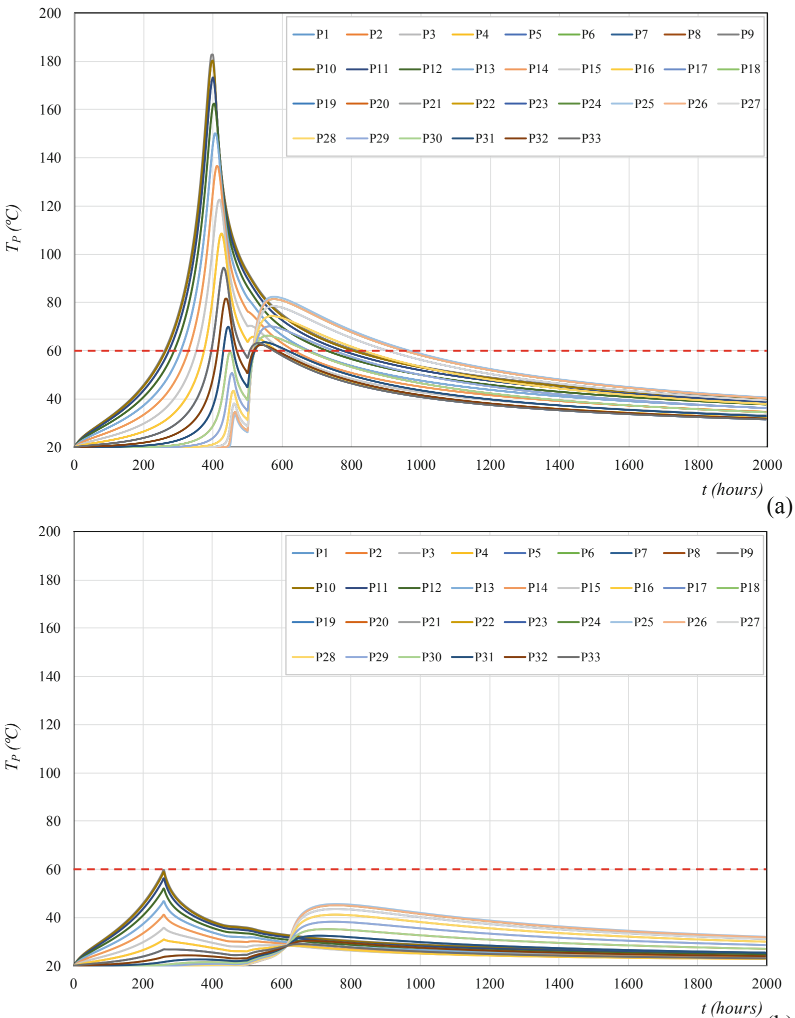

Fig. 4. Evolution of the field temperature distribution in the surface of the tree trunk: a) without; and b) with the use of the extinguished fire system. The red dashed line represents the lethal threshold ($T_P \leq 60$ °C).

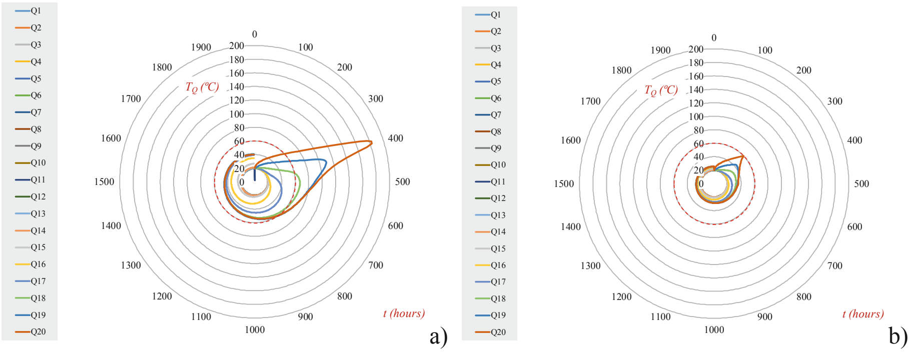

Fig. 5. Evolution of the temperature distribution in the points Q1–Q20 located on the tree trunk radius containing P9: a) without; and b) with the use of the extinguished fire system. The red dashed line represents the lethal threshold ($T_Q \leq 60$ °C).

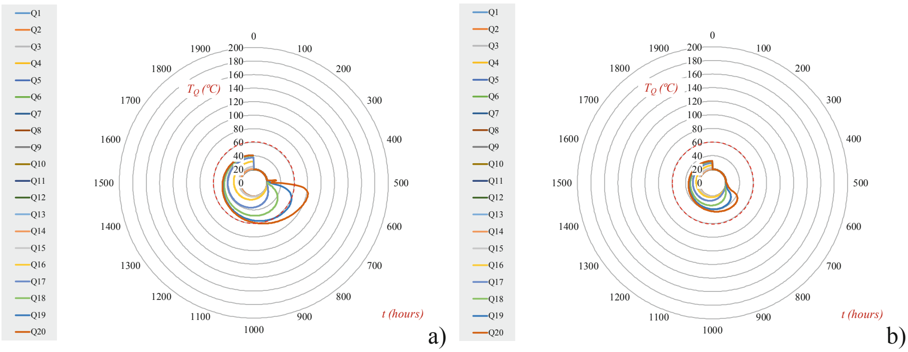

Fig. 6. Evolution of the temperature distribution in the points Q1-Q20 located on the tree trunk radius containing P25: a) without; and b) with the use of the extinguished fire system. The red dashed line represents the lethal threshold ($T_Q \leq 60$ °C).

Regarding to the thermal behavior inside the tree (Fig. 5 and Fig. 6), it is verified that, when the fire extinguishing system is deactivated, on the upstream side of the tree, points located up to the second outermost ring will reach temperatures above 60 °C; on the downstream side of the tree, only points located in the outermost ring will reach this temperature. In the upstream side, the highest temperature (182.6 °C) is obtained at point Q20 (coincident with P9), while in the downstream side the highest temperature (82.4 °C) is obtained at point Q20 (coincident with P25). With the operation of the fire extinguishing system, all temperatures inside the tree trunk are below 60 °C.

5 Conclusions

In this article, the results of a numerical simulation on the action of a fire extinguishing system installed in a tree were presented when a forest fire approached. As a reference, the situation in which the fire extinguishing system is not used was analyzed.

The main conclusions obtained are as follows:

- When the fire extinguishing system is not used the entire outer surface as well as points up to the two outermost rings of the tree will reach temperatures above 60 ºC causing the death of its tissues;
- With the operation of the fire extinguishing system, all points located in the tree will have temperatures below 60 ºC;
- The fire extinguishing system works as soon as the first point located on the tree reaches 60 °C and for as long as necessary to keep all other points below that value.

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