Chapter 8
Numerical Evaluation of the Temperature Distribution in a Tree Trunk in a Forest Fire Environment

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Abstract The numerical simulation presented in this paper is focused on the development of a numerical model used to calculate the evolution of the temperature distribution in a tree trunk when it is affected by the passing of a fire front. The purpose is to assess which points on the tree trunk exceed the tree lethal threshold. Heat conduction inside the trunk tree, heat convection between the tree trunk surface and the air environment and heat exchange by radiation between the trunk surface and the surrounding body surfaces are thermal phenomena considered in the numerical model. The case considered in the numerical simulation is characterized by the propagation of a fire front at a constant fire spread rate from a distance of 5 m upstream of the tree trunk to a distance of 25 m downstream of the tree trunk. The tree trunk has a height of 2 m and a diameter of 0.3 m. The fire front has a flame temperature of 1000 °C, a fire spread rate of 0.01 m/s, a tilt angle of 45°, 10 m wide and 1.2 m high. The results obtained demonstrate that the tissues of the tree trunk located on its surface and in the first layers below its surface will die due to the temperatures calculated there being above the tree lethal threshold.

Keywords Front fire · Grid generation · Lethal threshold · Numerical simulation · Trunk tree

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8.1 Introduction

In Portugal, forests occupy about 39% of its mainland, with maritime pine ("pinus pinaster") being the predominant species (ICNF 2020). Portugal also has the highest incidence of forest fires in Europe (Botequim et al. 2017; Carvalho et al. 2010), with more than 20,000 occurrences of annual fires usually reported in previous years (Radovanovic et al. 2019). These forest fires cause negative impacts on "carbon storage, biodiversity conservation, hydrologic processes, and economic and social services" (Bowman 2009). It is therefore important to understand the behavior of fire and how it harms and kills trees. The mechanism of direct tree death from fire is the cambium necrosis via heat transfer by convection, conduction, and radiation to the crown, stem and root tissue (Sharon et al. 2018). All three processes can cause tree injury and mortality. The lethal threshold for trees is obtain for temperatures above or equal to 60 °C, although longer exposure at lower temperatures can also cause tissue death (Kelsey and Westlind 2017).

This article describes a preliminary study focused on the development of a model that calculates the evolution of the temperature inside the tree and thereby evaluating the points of the tree that equal or exceed the lethal threshold in the presence of a forest fire. The numerical model developed in this work is based on the geometry of the human body, applied on the model that simulates the thermal response of the human body. The application of this model can be seen in the studies by Conceição (Conceição 1999, 2000), Conceição and Lúcio (Conceição and Lúcio 2001, 2016), and Conceição et al. (Conceição et al. 2007, 2010a, 2013).

The numerical model analyzes the thermal behavior inside the tree using differential energy equations and the generalized mesh. At the boundary between the tree and the outside, the model considers energy balance equations: by conduction, with the interior of the tree; by natural, forced and mixed convection, between the surface of the tree and the outside environment; by radiation, between the surface of the tree and the surrounding environment and between the surface of the tree and the fire front.

In the calculation of radiative exchanges, a procedure similar to heat exchanges between surfaces inside building compartments is used. This procedure is implemented in the thermal response model of buildings with complex topology. Its application can be seen in the following works by Conceição et al. (Conceição et al. 2000, 2008, 2009, 2010b, 2018) and Conceição and Lúcio (Conceição and Lúcio 2009, 2010). In calculating the temperature distribution inside the tree an implicit model of finite differences is used.

The aim of this work is to apply a numerical model that uses adaptive mesh generation to determine the temperature field inside a trunk of a tree in transient conditions. The knowledge of this temperature distribution, caused by the presence of a forest fire front, will allow to identify the location of dead tissues inside the trunk due to the value of its lethal threshold having been reached.

8.2 Numerical Model

In the tree trunk, the following thermal phenomena are considered: heat conduction inside the tree, heat convection between the tree surface and the air environment and heat exchange by radiation between the trunk surface and the surrounding body surfaces, namely, the fire front, the fuel bed and the sky.

The hypothesis used to write the energy balance equations are the following:

- The heat flux is treated as two dimensional;
- The air temperature around the trunk, that is uniform and equal to the environment temperature, increases when the fire front approaches the tree;
- Use of heat transfer coefficients by convection developed for isothermal surfaces;
- The trunk is composed by bark and cambium;
- The fire effects around the trunk are not considered.

The type of grid used in the numerical simulation influences the results. In this study a numerical grid generation where the mesh is adapted to the body surface contours was developed using the finite difference method approach. In this adaptive grid generation, a physical space and a computational space were considered. The idea of this method consists of transforming the physical domain into the computational plan. This grid transformation is done by two elliptic partial differential equations, of Poisson's type. The adaptive grid generation used in this work can be seen in Fig. 8.1. The data input of this model are the wind speed, the fire front conditions (dimensions, inclination, flame temperature, fire rate spread), the tree dimensions, initial distance of the fire front from the tree and other initial conditions.

8.3 Numerical Methodology

The scheme of the forest fire scenery used in the numerical simulation is presented in the Fig. 8.2. This scheme is constituted by an inclined fire front, tree trunk and a fuel bed. Figure 8.2 also shows the symbology used in the representation of the wind speed (v_{air}), the fire spread rate (R), the dimensions of the fire front and the tree trunk. The fuel bed is considered to have finite dimensions $a \times b$.

The simulation analyzes the situation in which the fire front moves at a constant fire spread rate from a distance of 5 m upstream of the tree trunk to a distance of 25 m downstream of the tree trunk. The input data of the simulation are present in Table 8.1. The output data of the simulation are the temperature distribution obtained in a plane that cuts the tree at a height of 2 m at 30 points (P) equidistant distributed along the bark of the tree trunk, Fig. 8.3, and at 20 points (Q) distributed along the radius of the tree trunk, Fig. 8.4. In Fig. 8.4, the line of points chosen is in a plane perpendicular to the direction of propagation of the fire front.

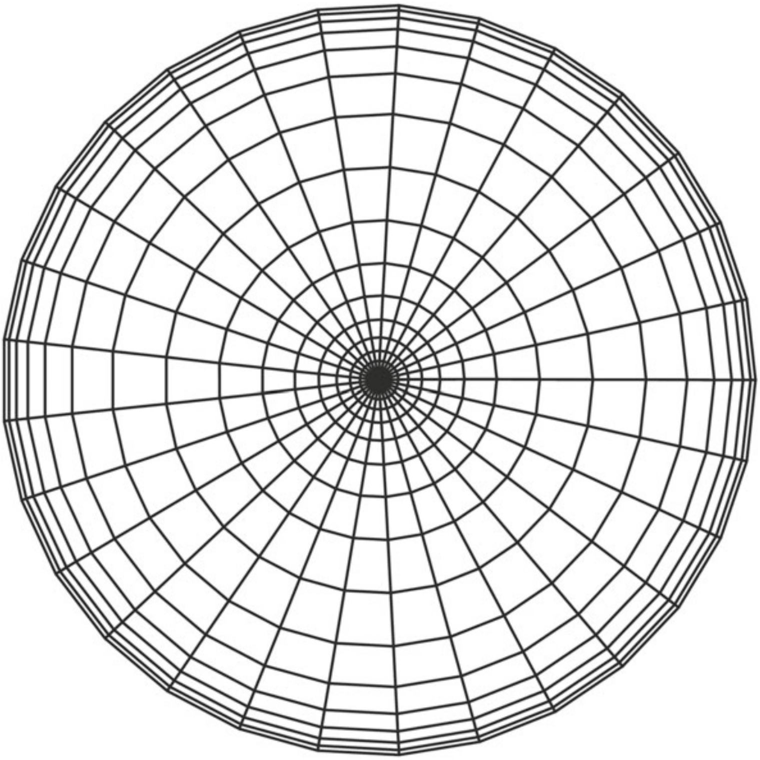

Fig. 8.1 Adaptive grid generation used in the tree trunk (30 × 20 grid points)

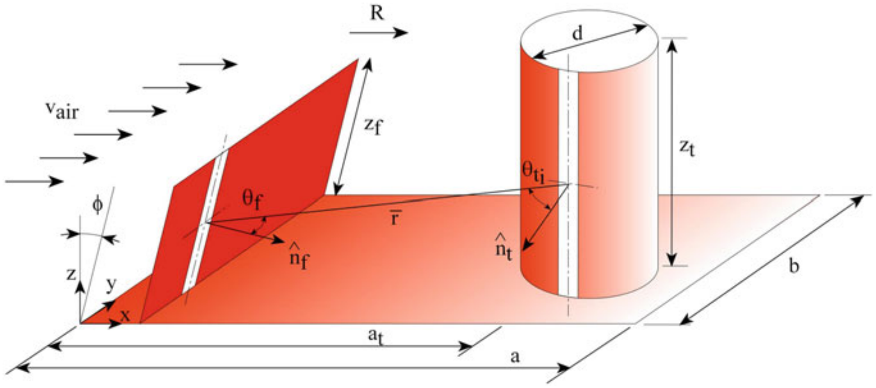

Fig. 8.2 Scheme of the forest fire scenery used in the numerical simulation

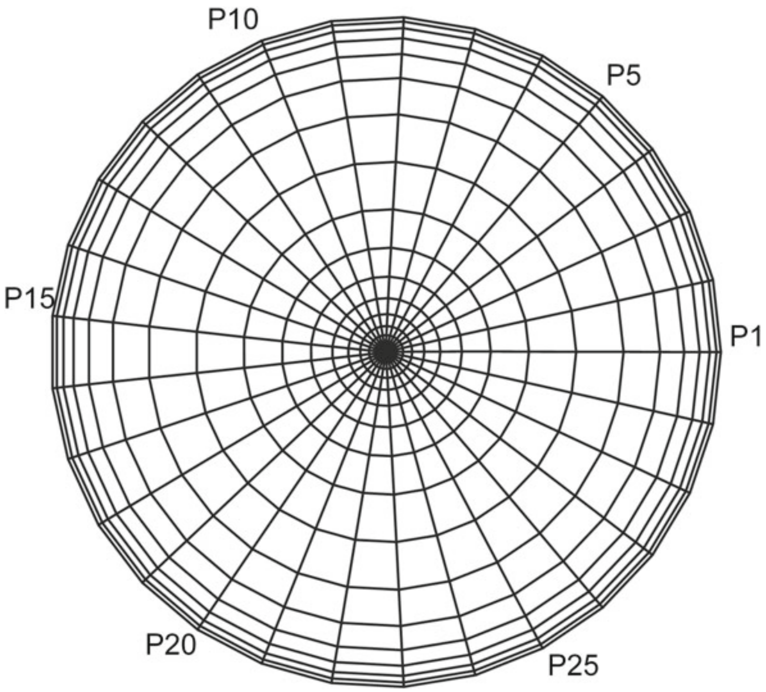

Fig. 8.3 Location of the 30 points distributed along the bark of the tree trunk where the temperature is numerically calculated

8.4 Results and Discussion

The evolution of the temperature values obtained at points P1–P15 (see Fig. 8.3), located on the bark of the tree trunk facing upstream of the fire front, can be seen in Fig. 8.5. The evolution of the temperature values obtained at points P16–P30 (see Fig. 8.3), located on the bark of the tree trunk of the beam downstream of the fire front, can be seen in Fig. 8.6. The evolution of the temperature values obtained at points Q1–Q20 (see Fig. 8.4), located on the line of the tree trunk radius, can be seen in Fig. 8.7. In Figs. 8.5, 8.6 and 8.7, the dashed line represents the tree trunk lethal threshold ($T_{trunk} \geq 60$ °C).

The temperature values in the tree trunk bark on the upstream side of the fire front are much higher when approaching than after the passage of the fire front. On the other hand, the temperature values in the tree trunk bark on the downstream side of the fire front are much higher after passing than when approaching the fire front. The temperatures reached are higher on the upstream side than on the downstream side of the fire front. The highest temperatures obtained in the tree trunk bark on the upstream and downstream side were, respectively, 515 °C and 276 °C. The lethal threshold of the tree trunk bark was reached more quickly on the upstream side than on the downstream side. All points on the upstream side reached the lethal threshold

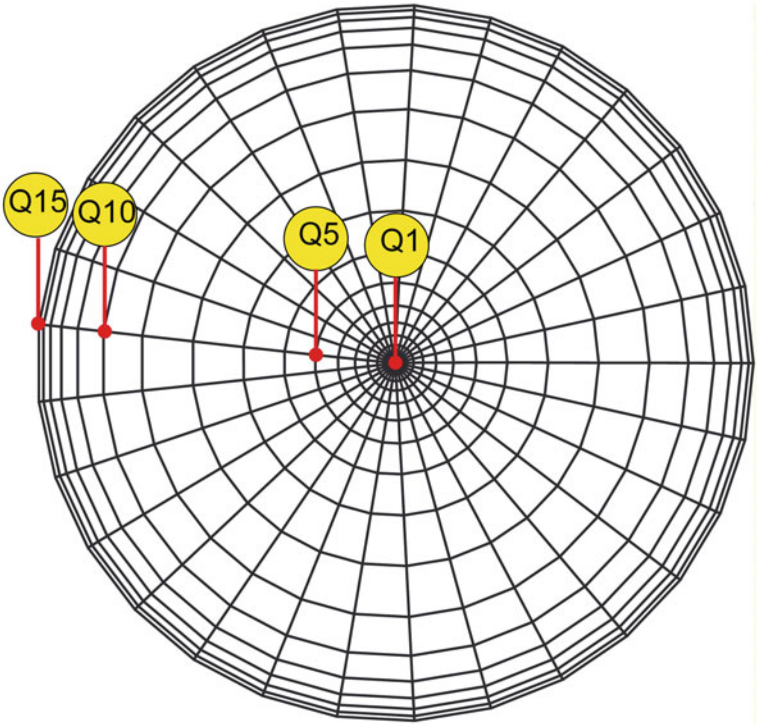

Fig. 8.4 Location of the 20 points distributed along the radius of the tree trunk where the temperature is numerically calculated

Table 8.1 Input data of the numerical simulation

Fire front	
Flame temperature (T_f)	1000 °C
Height (z_f)	1.2 m
Width (b)	10 m
Tilt angle (ϕ)	45°
Fire spread rate (R)	0.01 m/s
Tree Trunk	
Height (z_t)	2 m
Diameter (d)	0.3 m
Others	
Wind speed (v_{air})	0.1 m/s
Environmental air temperature (T_{air})	20 °C
Fuel bed length (a)	30 m

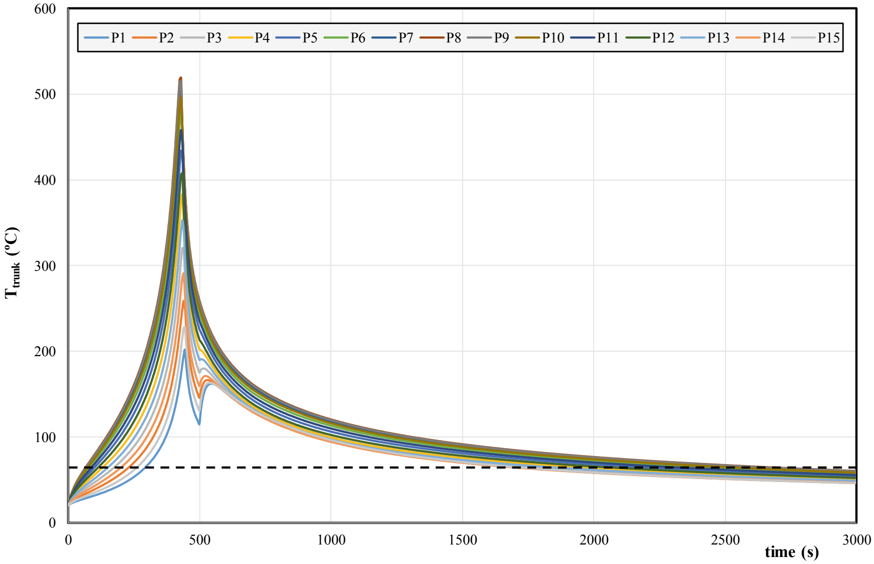

Fig. 8.5 Evolution of the temperature values obtained at points P1–P15, located on the bark of the tree trunk facing upstream of the fire front. The dashed line represents the tree trunk lethal threshold ($T_{trunk} \geq 60$ °C)

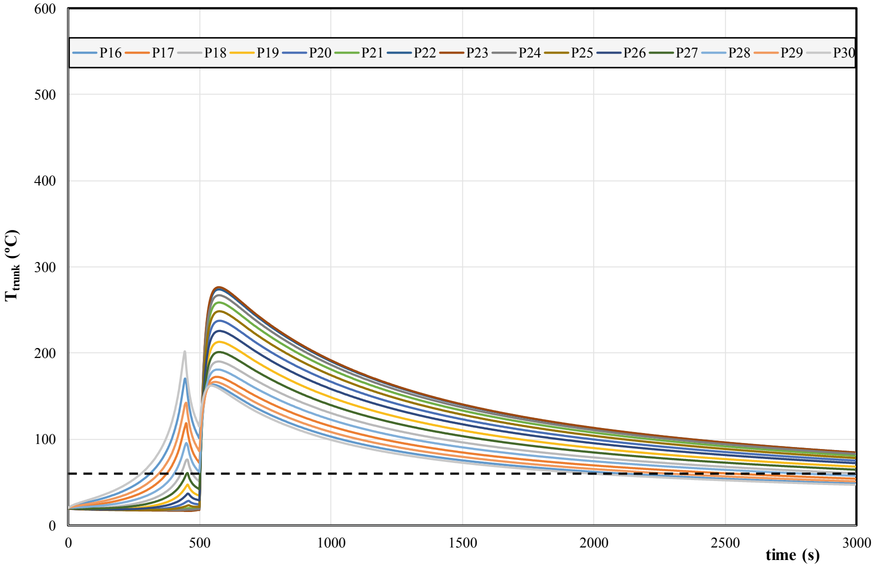

Fig. 8.6 Evolution of the temperature values obtained at points P16–P30, located on the bark of the tree trunk facing downstream of the fire front. The dashed line represents the tree trunk lethal threshold ($T_{trunk} \geq 60$ °C)

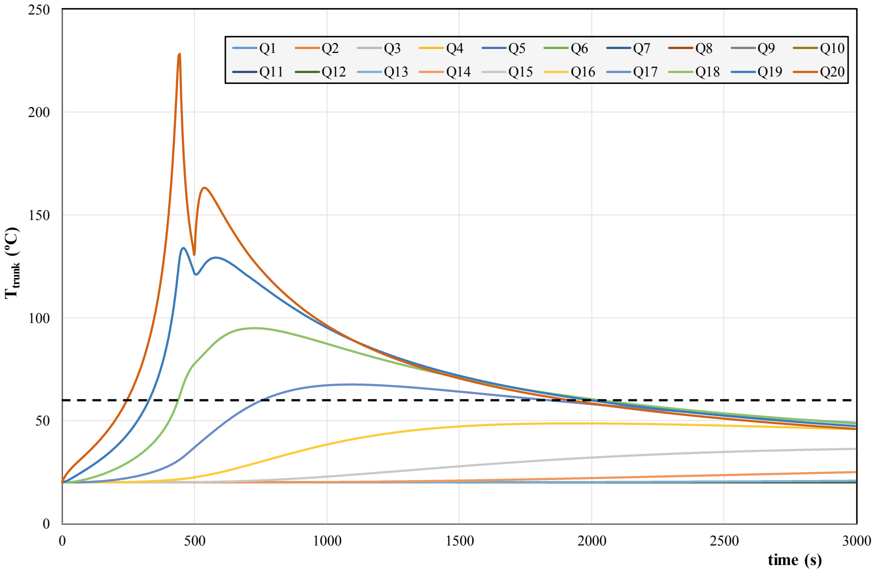

Fig. 8.7 Evolution of the temperature values obtained at points Q1–Q20, located on the line of the tree trunk radius. The dashed line represents the tree trunk lethal threshold ($T_{trunk} \geq 60$ °C)

before 280 s, while on the downstream side the lethal threshold was only reached on all points at 500 s of simulation time. The temperature at all points on the tree trunk bark upstream side drops below the lethal threshold after approximately 2500 s of simulation time. On the tree trunk bark downstream side, in general, after the passage of the fire front through the tree trunk, the temperature in almost all points remains above the lethal threshold during the simulation time.

The temperatures obtained in the core of the tree trunk are lower than those obtained in the tree trunk bark. The temperatures obtained in the outer rings of the tree trunk are higher than those obtained in the rings closer to the center of the tree trunk. The highest temperature (228 °C) was reached in the outermost ring of the tree trunk. The results of the temperature evolution obtained in points Q17–Q20 show that the lethal threshold is only reached in the 4 outer rings. The lethal threshold is reached in different simulation times; in the outermost ring of the trunk tree it is reached after about 60 s. The innermost rings of the trunk tree are little affected by the fire front, showing a temperature evolution around 20 °C.

The tree trunk before the progression of a fire front, with a flame temperature of 1000 °C, suffers different consequences and at different times: all the tissues of the bark die, while only the outermost tissues of the trunk die; the tissues of its bark die faster than those of its core; and the tissues of its bark upstream die faster than those of its bark downstream of the fire front.

8.5 Conclusion

This paper presents a preliminary study about the development of a numerical model used to calculate the evolution of the temperature distribution in a tree trunk in the presence of a fire front. Knowing this temperature distribution, it will be possible to identify the points on the tree that will reach the tree's lethal threshold and thus know the tree tissues that were damaged and those that died.

The main results obtained show that, in general, the temperatures in the tree trunk bark on the upstream side of the fire front are higher than that on the downstream side. The temperatures in the core of the tree trunk are lower than the temperatures in the tree trunk bark. The lethal threshold of the tree trunk is reached most quickly in its bark on the upstream side of the fire front. Only the points analyzed in the four outer rings of the tree trunk reach the lethal threshold.

Thus, it is confirmed that the area most damaged by the fire front is located on the surface of the tree trunk and in the first layers below its surface. In these areas the tree's tissues die. However, as only the most superficial layers of the tree trunk are severely affected, a good cleaning of the combustible material around the tree trunk and an efficient pruning of the tree trunk to a height of 2 m will allow the tree to recover from the damages suffered by forest fire.

In future works, the influence of the flame temperature, the fire spread rate, the wind speed, and others variables, on the temperature distribution in the tree will be analyzed.

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