COUPLING OF NUMERICAL MODELS OF MESH GENERATION AND HEAT TRANSFER OF A TREE TRUNK IN A FOREST FIRE ENVIRONMENT

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Abstract. This work presents a coupling between two numerical models, one for mesh generation and the other for heat transfer analysis, used to characterize the tree trunk thermal behaviour located in a forest fire environment. The geometry of the tree trunk is developed, using adaptive mesh generation, to evaluate the view factors, used to calculate the heat exchanges by radiation, between the virtual trunk tree and a fire front. The fire front represents the existing forest fire. The trunk tree thermal behavior numerical model is based on energy equations. The energy balance integral and differential equations consider the heat exchange by conduction inside the trunk tree, the heat exchange by convection between the trunk tree external surfaces and the environment and the heat exchanges by radiation between the trunk tree external surfaces and the environment and fire front. The numerical simulation is characterized by the propagation 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 trunk. With an irregular shape, the tree trunk has a height of 2 m and an external diameter of 0.2 m. The fire front has a tilt angle of 45º, 10 m wide and 2 m high. The temperature distribution in the tree trunk was obtained for a wind speed of 0.1 m/s, an average flame temperature of 500ºC, an environmental air temperature of 20ºC and an air relative humidity around the trunk tree of 50%. The temperature distribution obtained allows to identify the areas of the tree trunk tissues that were most affected by the passage of fire.

1 INTRODUCTION

Forest fires can cause significant changes on ecosystems. Its impacts have been increasing as the global temperature has increased due to climate change [1]. The fire front intensity and spread rate are two important fire behavior parameters. According to Blauw et al. [2], the moisture content, three-dimensional arrangement and mass of the fuel are the most important drivers of the fire spread and intensity of a forest fire. Forest fires can be divided into three categories, namely, crown fires, lethal understory fires and surface fires. Crown fires are relatively rare, but have higher severity and propagation spread rate than lethal understory and surface forest fires [3]. The tree flammability properties affect the tree response to fire. Its chance of survival reduces with increased flammability. Frejaville et al. [4] haveshownthatthebarkflammability of a tree reduces the potencial fortreesurvivalfollowingsurfacefires. Therefore, thebarkmust be slightlyflammableiftreeresistance to fireisprovidedby a thickinsulatingbark [4]. Experimentally, Jervis and Rein [5] investigated the differences in fire dynamics between live and dead Pinus needles. They concluded that not only moisture content is important in the burning behaviour of pine needles but also its chemistry and drying [5].

The numerical model of the tree trunk thermal response applied in this work is based on the numerical model of the human body thermal response. Both numerical models use energy balance equations in a similar way. The application of the numerical model of the human body thermal response can be seen in the studies of Conceição and Lúcio [6], and Conceição et al. [7,8].

The adaptive mesh is used by the numerical model to establish the differential energy equations that simulate the thermal behavior inside the tree trunk. The numerical model uses energy balance equations for boundary conditions. These equations describe the following heat transfer processes: by conduction inside the tree trunk; by convection (forced, natural or mixed) between the surface (bark) of the tree trunk and the surrounding environment; and by radiation between the surface (bark) of the tree trunk and the surrounding environment (including the fire front). The radiative exchanges between the tree trunk and the surrounding environment (including the fire front) are calculated using view factors. The procedure of this calculation is similar to that used to calculate heat exchanges inside the compartments. The model for calculating heat exchanges using view factors is one of the sub-models of the numerical model that evaluates the thermal response of buildings [9-16], and in the numerical model that evaluates the thermal behavior of passenger car cabinets [17].

The evaluation of the thermal response of a tree trunk located in a forest fire environment is done in this work. The objective is to characterize the level of damage of the tree's tissues by obtaining the distribution of temperatures on the surface and inside the tree trunk. The simulated situation considers a forest fire represented by a constant speed moving fire front. The fire front is moving towards the trunk tree, crossing it after a certain time.

2 NUMERICAL MODEL

The numerical model of this work is based on a coupling between two numerical models, one for mesh generation and the other for heat transfer analysis, used to characterize the tree trunk thermal behaviour located in a forest fire environment.

The results of the numerical simulation are influenced by the type of mesh used. In this work, it is used a mesh generation to adapt the body surface contours of the tree trunk. This adaptation is done using the method of finite differences [18]. The adaptive mesh generation consists of transforming the physical domain into a computational domain, which is done by two elliptic partial differential equations, of Poisson's type. The adaptive grid generation used in this work can be seen in Figure 1.

The mesh generation is used to calculate the heat exchanges between the fire front and the trunk tree through view factors. The following thermal phenomena are considered for the tree trunk: heat conduction within the tree; heat convection between the tree surface and the environment; and heat exchange by radiation between the tree surface and the surroundings (fire front, fuel bed, sky). The following hypothesis are used to define the energy balance equations:

- The heat flux is two-dimensional;
- The air temperature around the tree trunk is uniform and the same as the environment temperature;
- Use of convection heat transfer coefficients developed for isothermal surfaces;
- The tree trunk is composed by bark and cambium;
- The action of fire around the tree is not considered.

This model has the following input data: wind speed; environmental temperature; fire front conditions (dimensions, tilt angle, flame temperature, fire rate spread); trunk tree dimensions; initial distance of the fire front from the tree; other conditions.
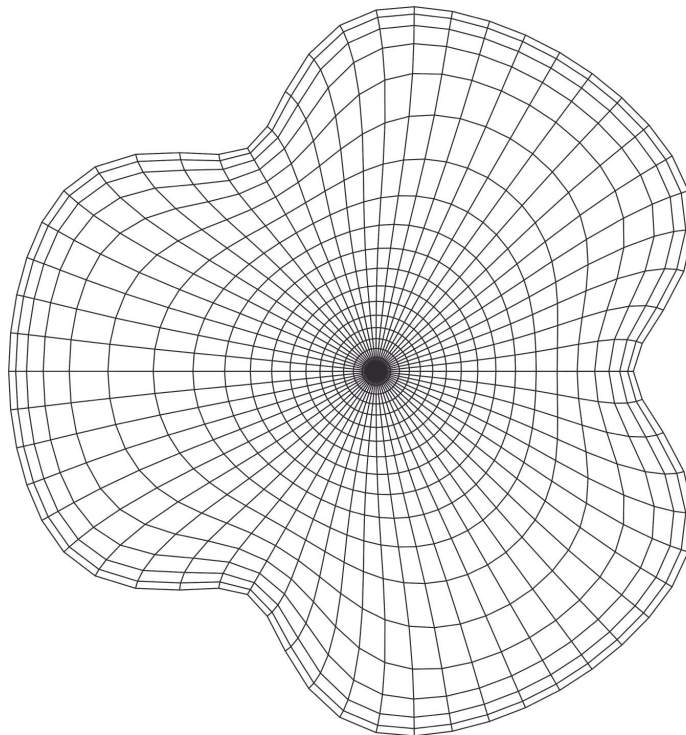
Figure 1: Adaptive grid generation used in the tree trunk (61 × 20 grid points).

3 NUMERICAL METHODOLOGY

The numerical simulation is characterized by the propagation 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 trunk. With an irregular shape, the tree trunk has a height of 2 m and an external diameter of 0.2 m. The fire front has a tilt angle of 45º, 10 m wide and 2 m high. The temperature distribution in the tree trunk was obtained for a wind speed of 0.1 m/s, an average flame temperature of 500ºC, an environmental air temperature of 20ºC and an air relative humidity around the trunk tree of 50%. The temperature distribution was obtained in a plane that cuts the tree at a height of 2 m at 61 points (P) equidistant distributed along the external surface (bark) of the tree trunk and at 20 points (Q) distributed along the radius of the tree trunk, as it is shown in Figure 2.
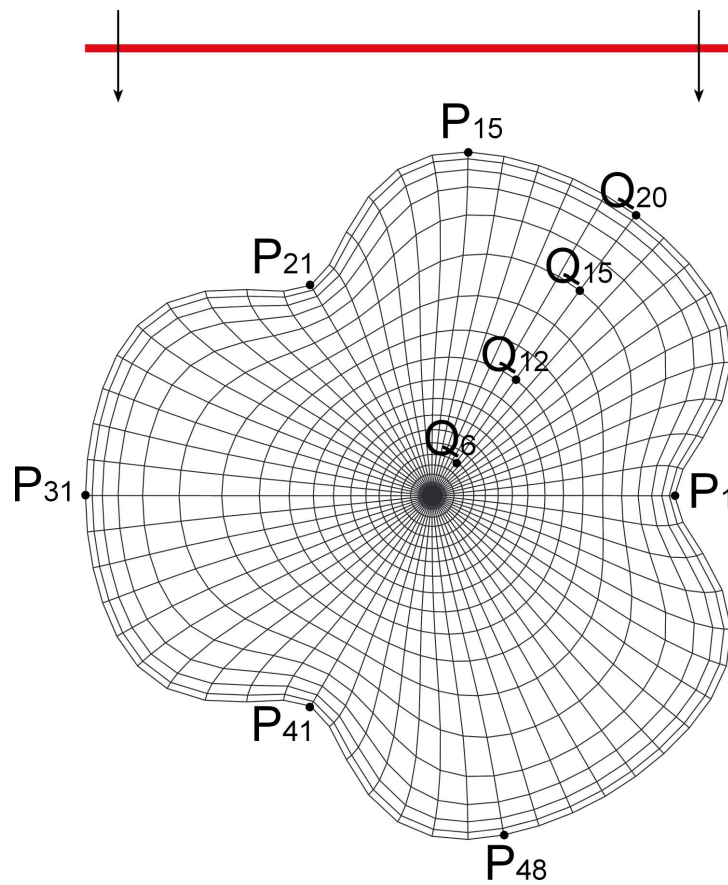

Figure 2: Location of the 61 P-points equidistant distributed along the bark of the tree trunk and the 20 Q-points distributed along the radius of the tree trunk. The red line represents the fire front.

4 RESULTS AND DISCUSSION

The evolution of the temperature distribution in the tree trunk, over time, is presented in Figure 3. In the initial instant, the fire front is 5 m upstream of the tree trunk.

The results show that the sections of the tree trunk most affected by the moving fire are

mainly situated on the surface (bark and outermost ring). The highest temperatures are reached after around 400 s when the fire comes from the upstream side of the tree trunk, due to the inclination of the fire front. The temperatures are lower on the downstream side of the tree trunk due to the radiative exchanges with the fire front are of small amplitude. The lateral sections of the tree trunk are also little influenced by the moving fire, because the heat exchanges by conduction between the surface and the interior of the tree trunk are of little value. The cooling period is slower than the heating period, being longer on the upstream side than on the downstream side of the tree trunk. The lateral sections of the tree trunk have almost cooled down to close to 20ºC at the end of 1800 s.


t = 300 s   t = 400 s

t = 600 s   t = 800 s

t = 1000 s   t = 1200 s
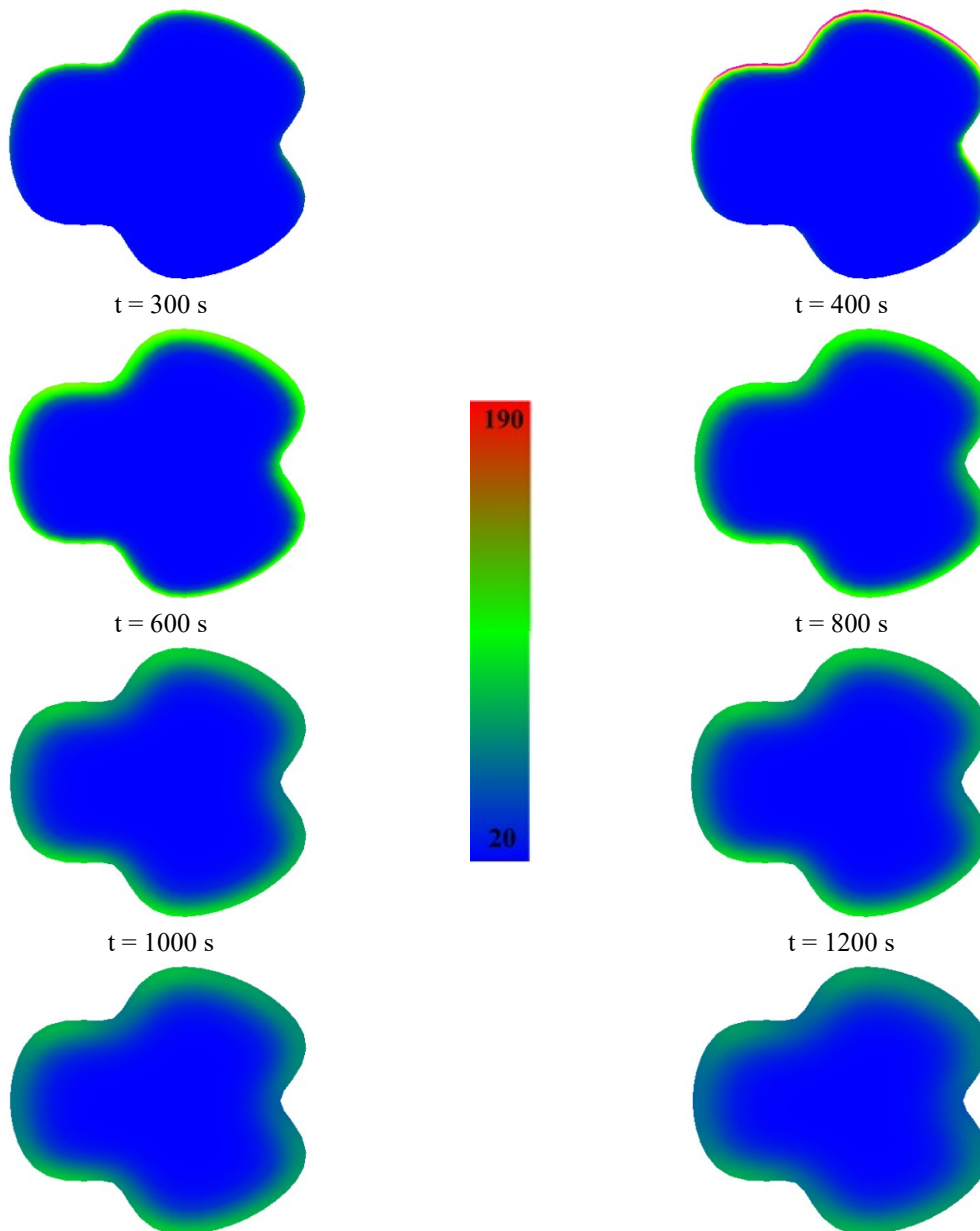
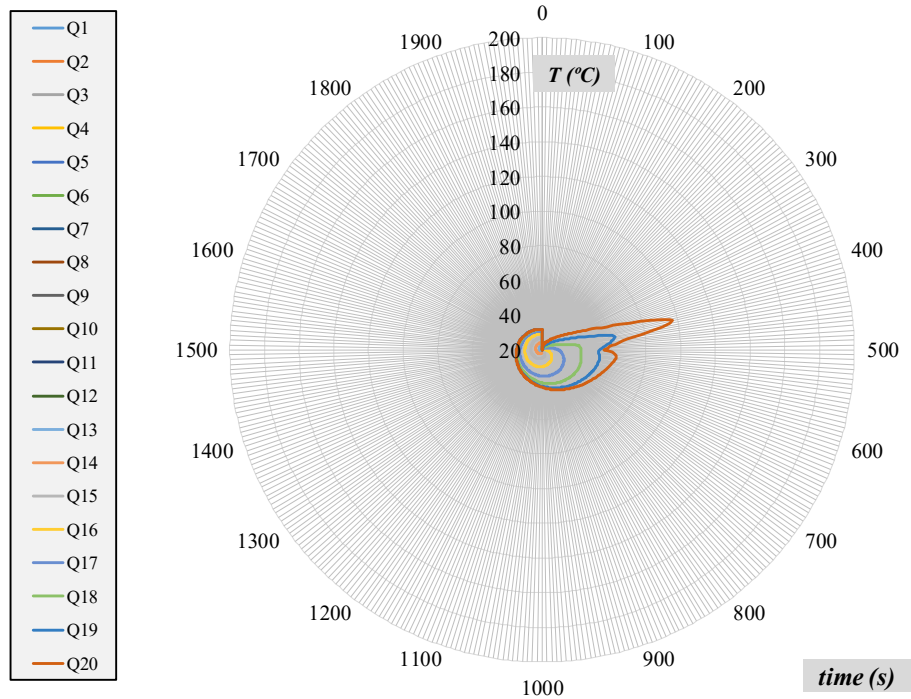t = 1400 s   t = 1800 s

Figure 3: Evolution of the temperature distribution in the tree trunk.

The evolution of the temperature values obtained at selected P-points of the tree trunk is presented in Figure 4. In Figures 5 to 7, it is presented the evolution of the temperature at the points Q1-Q20 located on the line of the tree trunk radius which contains the selected P-points number 1, 15, 21, 31, 41 and 48.
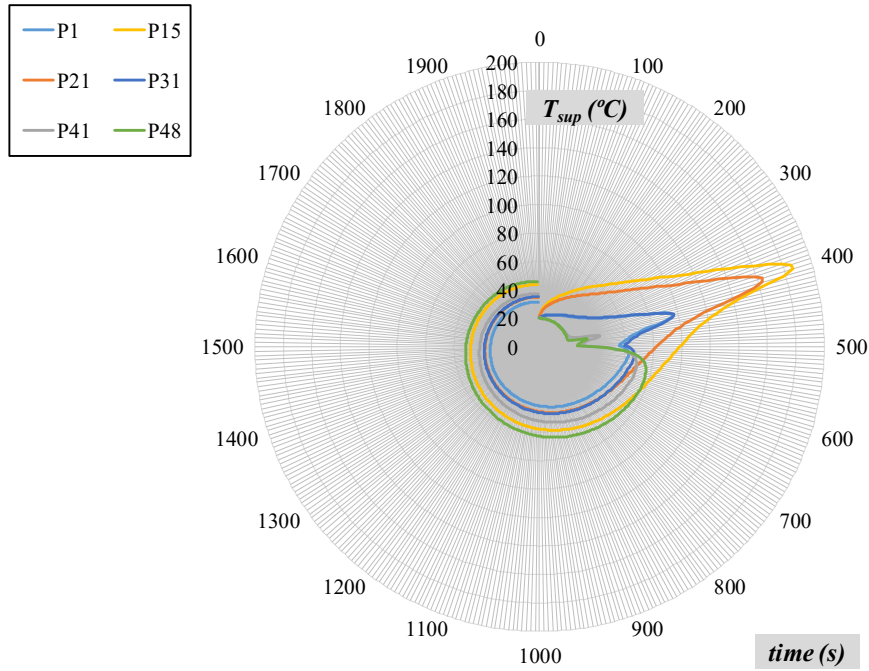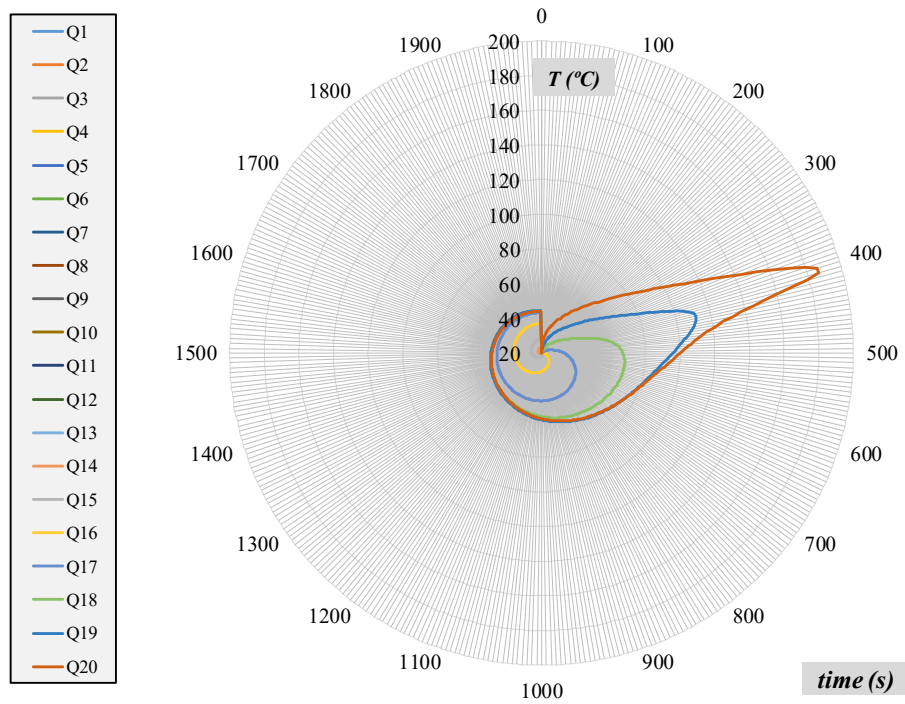

Figure 4: Evolution of the temperature at selected P-points.

Regarding to the results, the temperature reaches higher values in the tree trunk bark upstream of the fire front than downstream of the fire front. The highest temperature of about 190ºC is reached at the point P15 in the bark of the pine tree trunk facing upstream of the fire front. This value is obtained about 400 s of simulation time. Downstream of the tree trunk, the maximum temperature value of around 77ºC is obtained at point P48 after about 600 s of simulation time. At the end of the simulation time (2000 s), the temperature in the bark of the tree trunk tends to values around 30-40ºC.

Inside the pine tree trunk, the temperature reaches higher values at its outermost points. In general, temperatures take values above 60ºC in the two or three outermost rings. These values occur for about 700 s for the most adverse situations. In the outermost ring, the maximum temperature of around 112ºC is obtained after 430 s of simulation time. At the end of the simulation time, all temperatures inside the tree trunk are below 40ºC.
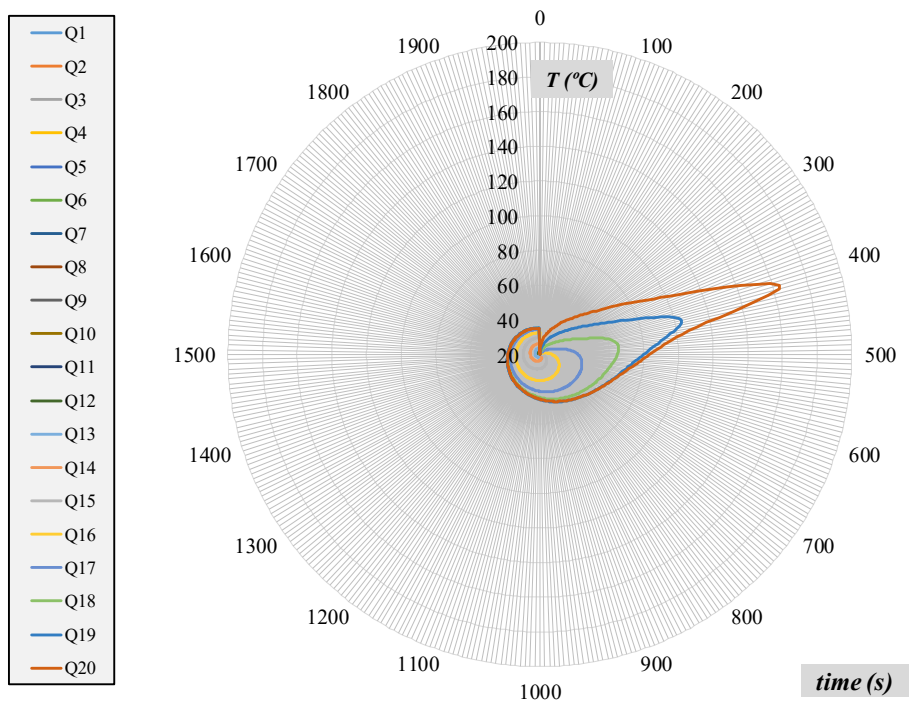
P1

P15

Figure 5: Evolution of the temperature at the points Q1-Q20 located on the line of the tree trunk radius which contains the selected P-points 1 and 15.
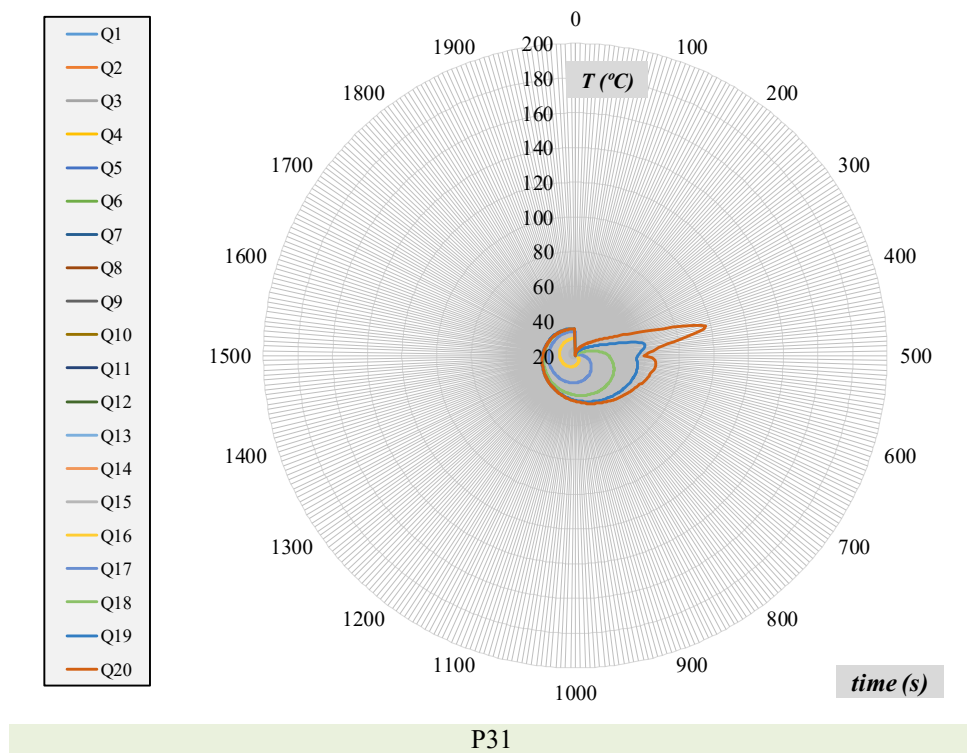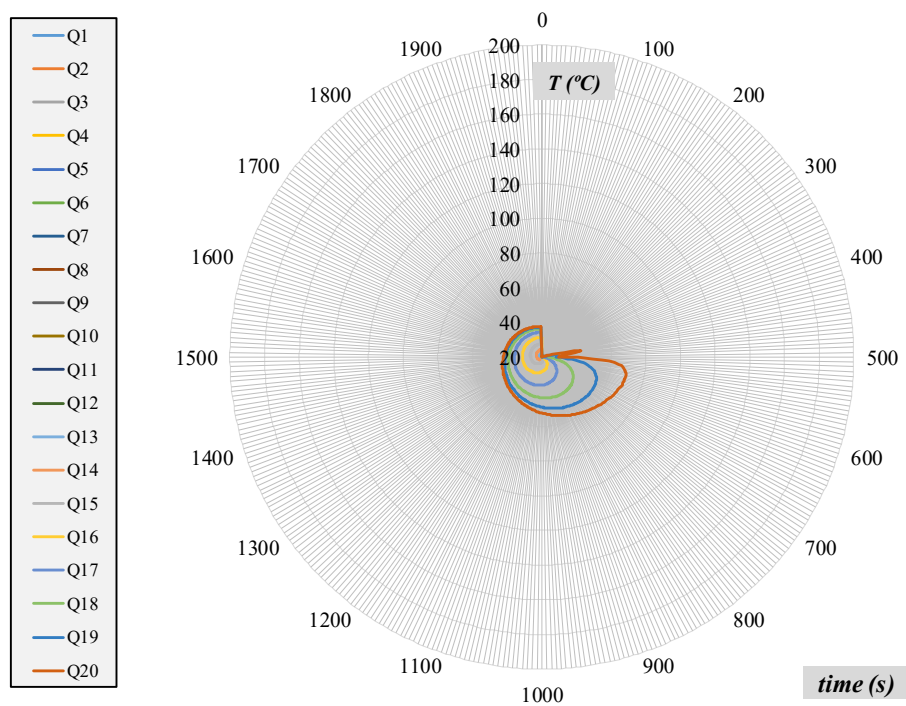

P21

P31

Figure 6: Evolution of the temperature at the points Q1-Q20 located on the line of the tree trunk radius which contains the selected P-points 21 and 31.
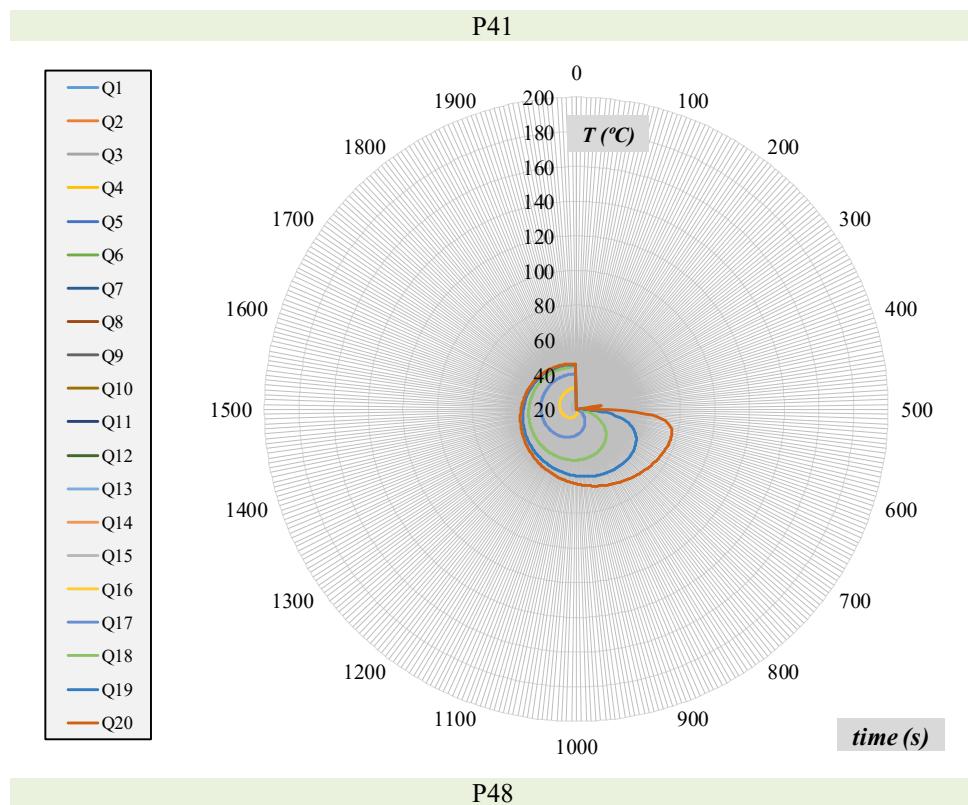
Figure 7: Evolution of the temperature at the points Q1-Q20 located on the line of the tree trunk radius which contains the selected P-points 41 and 48.

5   CONCLUSIONS

In this numerical study, it was evaluated the influence of a forest fire, represented by a moving front fire, on the evolution of the temperature distribution in a trunk tree. The numerical simulation takes place over a period of time in which the fire front moves in the direction of the tree trunk from an initial position located 5 m downstream.

The results obtained for the temperature distribution show that the main sections of the trunk tree affected by the moving front fire are the bark and the two outermost rings. Due to the inclination of the flame, the upstream side reaches higher temperatures than the downstream side.

ACKNOWLEDGEMENT

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