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DOMINGOS XAVIER VIEGAS

LUÍS MÁRIO RIBEIRO

Two-dimensional model of heat transfer in a pine trunk under the influence of a forest fire environment

Eusébio Conceição*[1]; João Gomes[2]; Mª Manuela Lúcio[1]; Domingos Viegas[3]; Mª Teresa Viegas[3]

[1] *FCT – Universidade do Algarve, Campus de Gambelas,*
8005-139 Faro, Portugal, {econcei@ualg.pt, maria.manuela.lucio@gmail.com}
[2] *CINTAL, Campus de Gambelas,*
8005-139 Faro, Portugal, {jgomes@ualg.pt}
[3] *FCT – Universidade de Coimbra - Pinhal de Marrocos - Pólo II,*
3030 Coimbra, Portugal, {xavier.viegas, maria.viegas}@dem.uc.pt

**Corresponding author*

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Abstract

This article presents a numerical study on a two-dimensional model of heat transfers verified in a pine trunk under the effect of a forest fire. The thermal response model of the pine trunk was developed from a geometric model of complex topology of the trunk obtained using mesh generation. The thermal response model of the pine trunk is founded on energy energy balance integral and differential equations. Heat exchanges are considered by conduction inside the pine trunk, by convection between the outer surface of the pine trunk and the surrounding environment, and by radiation between the outer surface of the pine trunk and the and the surroundings, including the fire front. The radiative heat exchanges between the pine trunk and the fire front are calculated from the view factors obtained taking into account the meshing in the pine trunk and in the fire front. In this numerical study, it is considered that the fire front evolves with a spread rate with random and oscillatory characteristics, depending on wind speed, whose flame temperature has an average value of 500ºC. The evolution of the temperature distribution inside the pine trunk as well as in its outer surface was obtained for a variable and random wind speed. Temperature fluctuations on the outer surface of the trunk are affected by fluctuations in wind speed decreasing with time and with increasing distance from the fire front. Inside the trunk, temperature fluctuations occur mainly in the two outermost rings.

1. Introduction

The main influences on how fire spreads in forests are humidity, topography, wind and temperature (Tošić et al., 2019). The higher the temperature, the lower the humidity, and the lower the humidity, the drier the air, therefore dry fuel ignites and burns more easily. The slope of the landscape is also important: fires burn much faster uphill than downhill (Eftekharian et al., 2019). A fire creates radiation and convection phenomena that preheat the unburned fuel ahead of the fire front more effectively upslope than down. Fire spread is significantly affected by wind speed (Beer, 1991; Cruz and Alexander, 2019). Wind can bias fire behavior by moving moist air away from fuels, causing them to dry quickly. It transports burning embers that have been lifted aloft by convection air and starting spot fires ahead of the perimeter. It bends the convection column, which promotes preheating of unburned fuels in front of the fire. It brings a continuous supply of oxygen to the fire. Strong winds have a pressing dominant effect on the spread rate of wildfires when fuels are dry (Cruz et al., 2020). The environmental wind fluctuates in both direction and speed, with increased air instability implying greater fluctuations (Beer, 1991). Works on wildfire spread models (Nelson, 2002), simulations of spread and behavior of real fires (Jahdi et al., 2014), and fire spreads with variable wind strengths (Song and Li, 2017) present relevant aspects about the behavior of forest fires when under the effect of fluctuations in wind speed.

The numerical model used to simulate the pine trunk thermal response was founded on a numerical model used to simulate the human body thermal response (Conceição et al., 2010a; Conceição and Lúcio, 2016), because both models consider the use of energy equations in the boundary conditions in a similar way. These equations represent the following heat transfer processes: by conduction inside the pine trunk; by convection between the outer surface of the pine trunk and the surrounding environment; and by radiation between the outer surface of the pine trunk and the surroundings (fire front included). In the assessment of the radiative exchanges between the outer surface of the pine trunk and the surroundings is utilized view factors. The sub-model used in the calculation of the view factors was established in the same way as the sub-models used in the calculation of the view factors in buildings (Conceição and Lúcio, 2010; Conceição et al., 2010b) and in passenger compartments (Conceição et al., 2000).

The purpose of this numerical study is to present a model that simulates the transient thermal response of a pine trunk under the influence of a forest fire, considering the variable wind speed. The forest fire is represented by a front fire with a variable spread rate. The transient thermal response will be assessed by the temperature distribution evolution inside and on the outer surface of the pine trunk.

2. Numerical Model

The differential energy equations and the generated mesh are utilized by the numerical model to evaluate the thermal response of the pine trunk, which consists of bark and cambium. This numerical model takes into account energy balance equations at the boundary between the pine trunk and the surrounds assuming the following thermal phenomena: heat conduction inside the pine trunk, heat convection (natural, forced and mixed) between the outer surface (bark) and the environment air and heat exchange by radiation between the outer surface (bark) and the surrounding body surfaces (fire front, fuel bed and sky).

These energy balance equations are established considering the following hypotheses:

- The heat flux is defined in two dimensions;
- The air temperature around the pine trunk, uniform and equal to the ambient temperature, will increase as the fire front approaches its vicinity;
- Use of heat transfer coefficients by convection developed for isothermal surfaces;
- The effects of fire around the pine trunk are neglected.

In the generation of the mesh of the pine trunk and fire front, the finite differences method is used. The numerical mesh generation considers a physical space and a computational space. The model transforms the physical domain into the computational plan, using two elliptic partial differential equations, of Poisson's type.

3. Methodology

The results of the numerical simulation will be the evolution of the temperature distribution inside and on the outer surface (bark) of the pine trunk obtained in a transient regime. In the numerical simulation carried out, it was considered that the wind speed is variable according to the profile represented in Figure 1, with an average value of 5.04 m/s.

The fire front progresses with a variable fire spread rate, according to the profile shown in Figure 2, with an average value of 0.0116 m/s, from a distance of 10 m upstream of the pine trunk. The pine trunk has a height of 2.0 m and an external diameter of 0.4 m. The fire front has a tilt angle of 70º relative to the ground plane, 2 m wide, 4 m high and an average flame temperature of 500ºC. The representation of fire propagation towards the pine trunk is shown in Figure 3. As environmental conditions, there is an air temperature of 20ºC and a relative humidity of 50% near the trunk. The temperature distribution was obtained at 33 points (P) equidistant distributed along the outer surface (bark) of the pine trunk in a plane located at a height of 2.0 m and at 20 points (Q) distributed along the radius of the pine trunk, as shown in Figure 4.

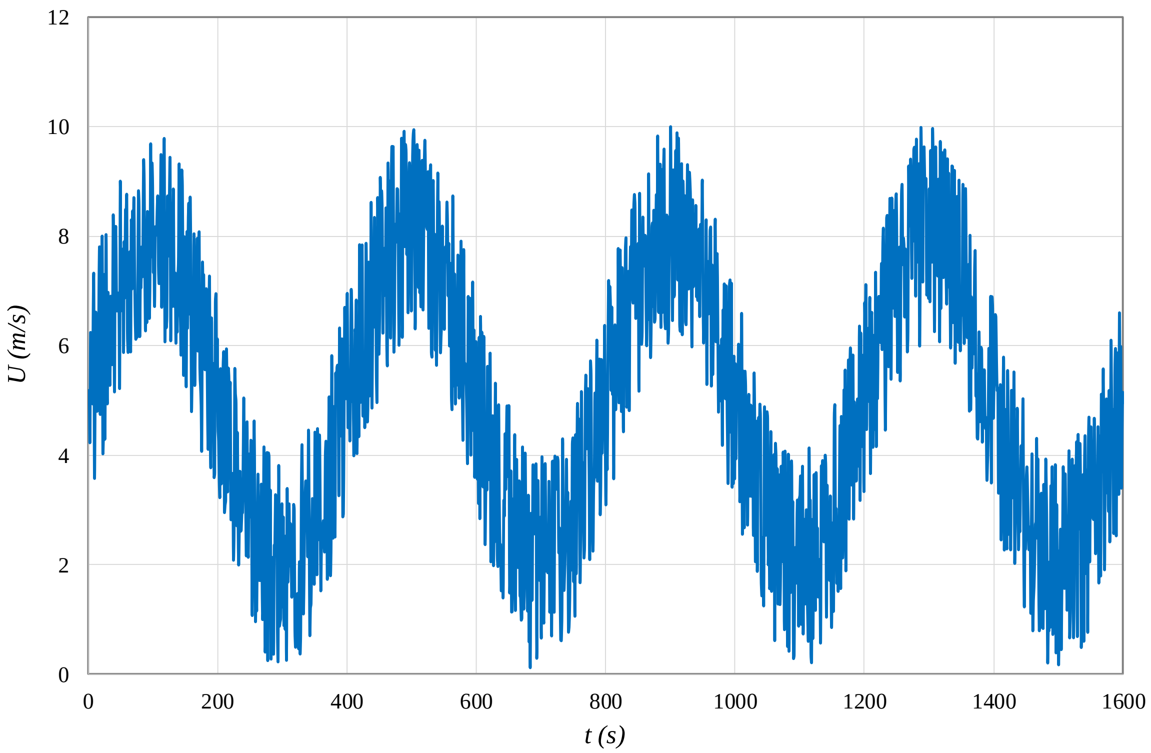

Figure 1 – Profile of wind speed.

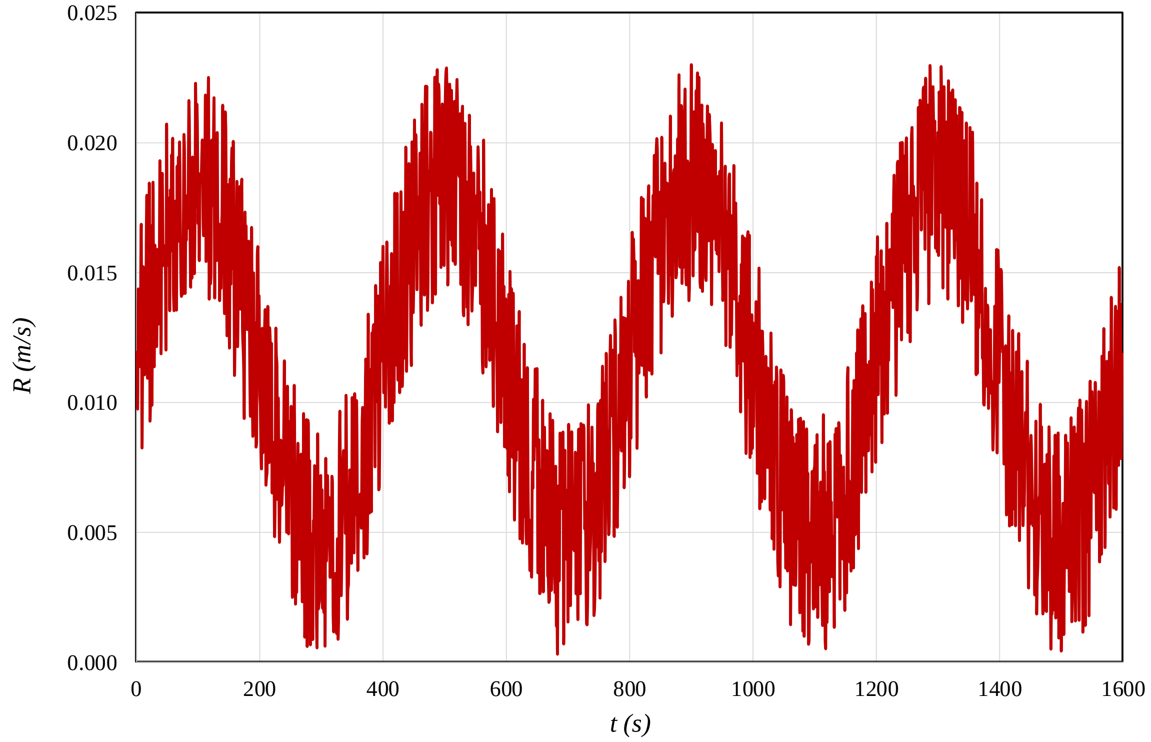

Figure 2 – Profile of fire spread rate.

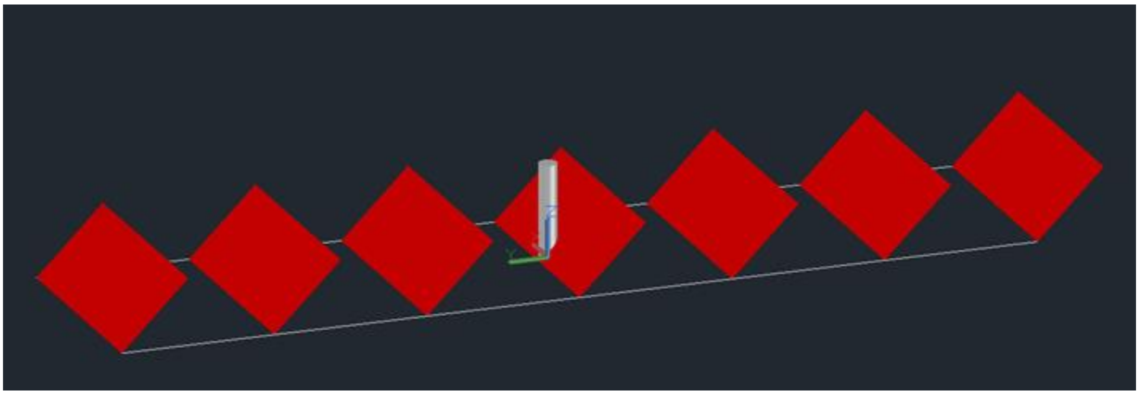

Figure 3 – Representation of the movement of the fire front towards the pine trunk.

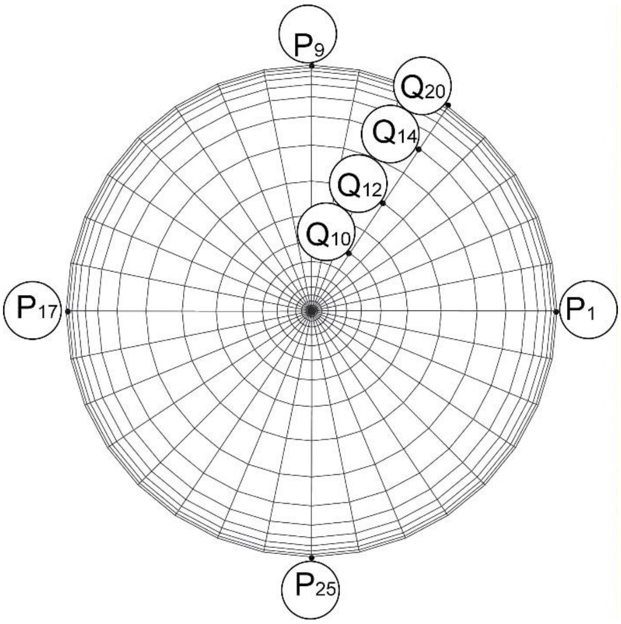

Figure 4 – Cross-section of the pine trunk with the location of the 33 P-points on its outer surface (bark) and the 20 Q-points on its interior.

4. Results and Discussion

The evolution of the temperature distribution on the outer surface (bark, points P1 to P33) of the pine trunk is shown in Figure 5. The results show that during the movement of the fire front, the upstream side of the pine trunk is the first to be affected by the increase in temperature on its outer surface. Fluctuations in wind speed and, consequently, in the fire spread rate, cause fluctuations in the temperature obtained at the marked points on the outer surface of the trunk. The maximum values of temperature fluctuations, as well as the amplitudes of these fluctuations, decrease with time and with the distance of the fire from the pine trunk. Temperatures are higher on the upstream side of the tree trunk than on the downstream side due to the slope of the flame caused by the spread of fire.

The evolution of the temperature distribution in the points Q1-Q20 located on the interior of the pine trunk, containing the point P1 on the side, on the upstream side, the point P9 on the upstream side and the point P25 on the downstream side (see Figure 4), is shown, respectively, in Figure 6, Figure 7 and Figure 8.

As can be seen from the temperature variation in relation to the ambient temperature of 20ºC, fire influences the four outermost rings, mainly the two rings represented by points Q18 and Q19. In these two rings, fluctuations in wind speed and fire spread rate have a noticeable impact on the fluctuations obtained in the evolution of temperature. Therefore, it can be seen that the passage of a forest fire with the characteristics presented here can cause the interior areas of the trunk to heat up to values around 60ºC on its upstream side.

Temperatures of 60ºC can cause the death of tree tissues (Kelsey and Westlind, 2017). Inside the trunk, temperatures are generally higher at points located on the upstream side of the trunk than on the downstream side. Again, this is due to the way the flame leans in the downstream direction of the fire's movement.

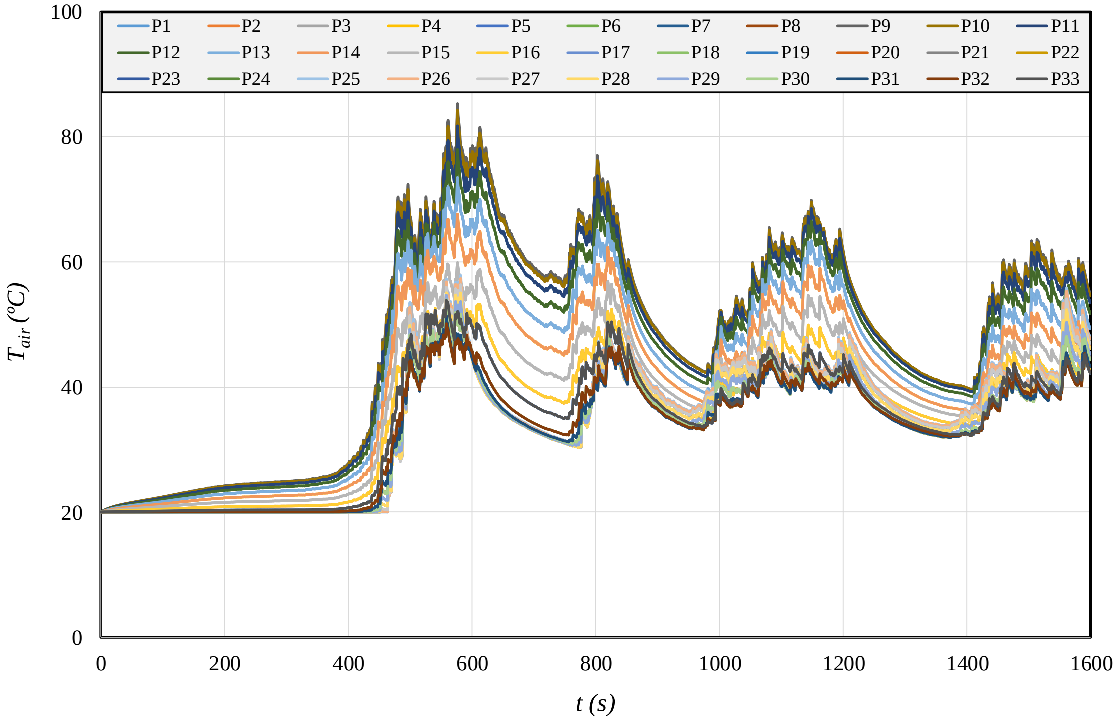

Figure 5 – Evolution of the temperature distribution on the outer surface (points P1 to P33) of the trunk according to the environmental conditions in which the fire propagates.

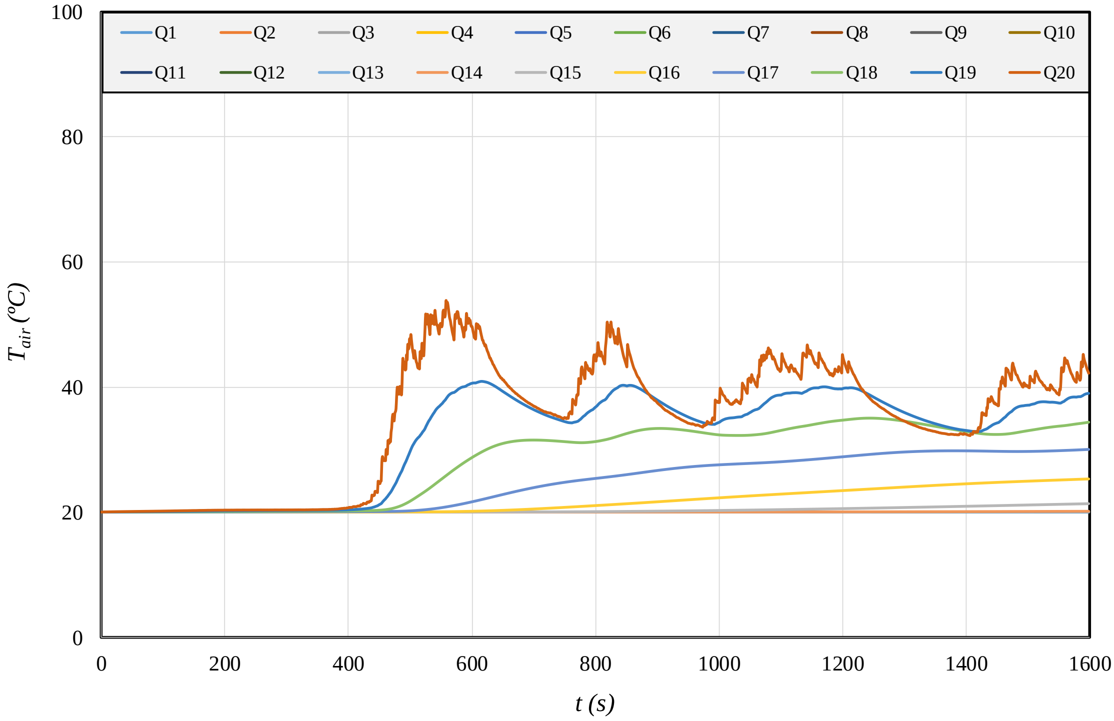

Figure 6 – Evolution of the temperature distribution in the points Q1-Q20 located inside the pine trunk containing the point P1 (coincident with point Q20) on the outer surface.

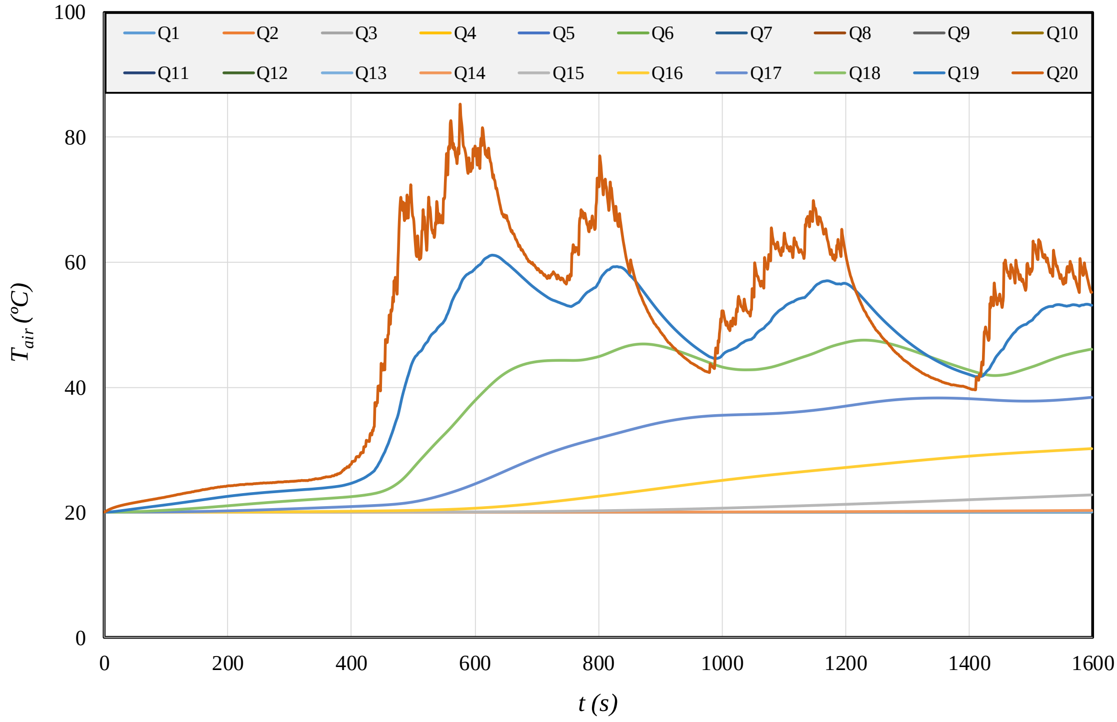

Figure 7 – Evolution of the temperature distribution in the points Q1-Q20 located inside the pine trunk containing the point P9 (coincident with point Q20) on the outer surface.

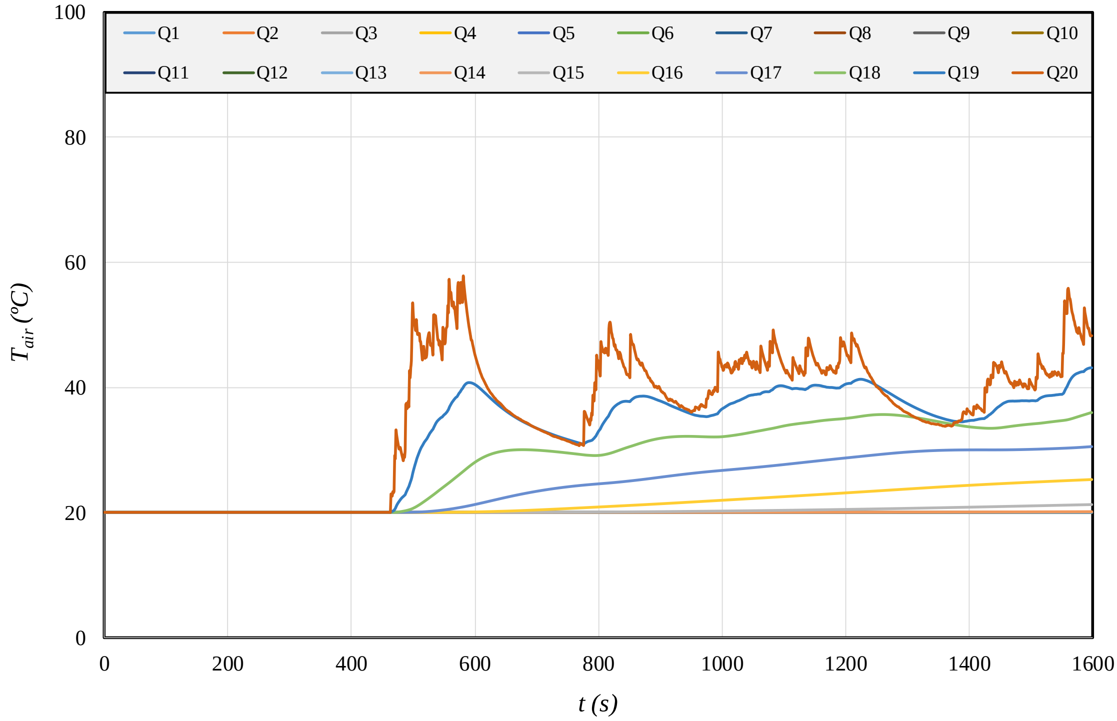

Figure 8 – Evolution of the temperature distribution in the points Q1-Q20 located inside the pine trunk containing the point P25 (coincident with point Q20) on the outer surface.

5. Conclusions

The thermal response of a pine trunk under the influence of a forest fire was numerically evaluated in this article. Forest fire is represented by a moving fire front. The temperature distributions inside and on the outer surface of the pine trunk were obtained in a transitory regime. The numerical study was carried out assuming that the wind speed and the fire spread rate have a random evolution.

The results show that fluctuations in wind speed and fire spread rate also cause fluctuations in temperature calculated at points on the outer surface and in the four outermost rings of the pine trunk. At points on the outer surface, the maximum temperature values and the amplitudes of temperature variations decrease with time and with increasing distance from the fire to the pine trunk. Inside the trunk, on the upstream side, there are points on its outermost ring that reach 60ºC, which can cause tissue death there. Points on the upstream side of the pine trunk have higher temperatures than those on its downstream side due to the inclination of the flame in the direction of fire movement downstream of the pine trunk.

6. Acknowledgments

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