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GRID GENERATION AND HEAT TRANSFER IN A COMPLEX TOPOLOGY MARITIME PINE TREE IN FOREST FIRE ENVIRONMENTS

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Abstract. This article presents a study on the grid generation and heat transfer in a complex topology maritime pine tree in a forest fire environment. The numerical model of the maritime pine tree thermal behaviour is developed and applied. This numerical model is based on energy balance integral equations for the maritime pine tree elements. These equations are obtained for the heat exchanges by conduction within the maritime pine tree elements, by convection between the external maritime pine tree surfaces and the environment, and by radiation between the external maritime pine tree surfaces and the fire front. The geometry of the virtual maritime pine maritime pine tree was here developed applying mesh generation, which is used to evaluate the view factors. In turn, these view factors are used to calculate the heat exchanges by radiation between the virtual maritime pine tree and the fire front. The virtual maritime pine tree geometry is constituted by 8863 cylindrical elements, which represent their trunks, branches and leaves, and it is divided into four levels. The input data considered in the numerical simulation are the mean flame temperature of 500ºC, the air temperature of 20ºC, the wind speed of 10 m/s and the air relative humidity around the pine tree of 50%. The numerical simulation results are the view factors and the evolution of the surface temperature of the maritime pine tree elements obtained in a transient regime. The values of the view factors and the surface temperature of the maritime pine tree elements decrease from the first level, near the ground, to the last level, at the top of the maritime pine tree. The stabilization time of the surface temperatures of the maritime pine tree elements decreases according to the increase of the height to which these elements are located.

1 INTRODUCTION

Maritime pine tree ("pinus pinaster") is one of the most abundant tree species in Portuguese forests and also one of the species that most burns due to forest fires [1]. The numerical study of the thermal behavior of the maritime pine tree is therefore important because it will allow to know and better understand its performance and later conditions when facing a forest fire. This paper presents a study on the development of the geometry of a virtual pine tree based on mesh generation. From this geometry, the necessary view factors will be determined to calculate the temperature distribution on the surfaces of the constituent elements of the pine tree.

The maritime pine thermal response model is based on thermal and radiative numerical models previously developed and applied in the evaluation of thermal response of vehicles [3], buildings [4], human thermo-physiology [5], etc. The finite elements theory was used on the mesh generation of the geometry of the vehicle, building or human body, implemented in these models. The validation of the building thermal response model was done in Conceição and Lúcio [5], for summer conditions. The validation of the human thermal response model was done in Conceição and Lúcio [6].

The radiative heat exchanges are important in the studies of forest fires to analyze the thermal interaction between the tree and the fire front. The use of mesh generation in the radiative heat exchanges can be seen in the works of Conceição and Lúcio [7] and in Conceição et al. [8]. Additional applications of the thermal response model can be noted in Refs. [9-16], for buildings, and in Refs. [17,18], for persons.

As purpose, this work applies a numerical model to generate a mesh, which represents the geometry of a virtual maritime pine tree, followed by the calculation of the view factors between the outer surface of the maritime pine tree and a static fire front located nearby. These view factors will be used by the numerical thermal response model to obtain the Mean Radiant Temperature (MRT) and the transient surface temperatures of the various elements (trunks, branches and leaves) of the virtual maritime pine tree.

2 NUMERICAL MODEL

The numerical model is based on mesh generation, which is used to calculate the geometry of the maritime pine tree and the heat exchanges between the fire front and the maritime pine tree.

The definition of the maritime pine tree geometry, namely the main and secondary trunks and branches, is carried out through cylinders. Each cylinder is characterized by the diameter, height, rotation of a *beta* angle around the Y-axis and rotation of a *gamma* angle around the Z-axis.

In defining the geometry of the maritime pine tree, two references are considered:

- Global reference x, y, z (see Figure 1a), where all coordinates are defined in the maritime pine tree and in the fire front;
- Particular reference x ', y', z ', where all coordinates are defined in relation to each of the cylinders.

The fire front also needs to be defined geometrically. In this case, it is a flat surface characterized by height, width, rotation of a *beta* angle around the Y-axis and rotation of a *gamma* angle around the Z-axis.

In the mesh generation around each of the cylindrical elements of the maritime pine tree, a mesh with *n* divisions according to angles and *m* divisions according to length is considered. In the case of the fire plane, a mesh with *p* divisions according to length and *q* divisions according to height is considered.

The maritime pine tree thermal response numerical model takes into account the phenomena of radiation, conduction and convection and it is based on energy balance integral equations (equation (1)). These equations are developed for:

- Different cylindrical layers of the main trunks;
- Different cylindrical layers of the secondary trunks;
- Different cylindrical layers of the branches;
- Different cylindrical layers of the leaves.

$$mCp\frac{dT}{dt} = \sum_i \dot{Q}_i \qquad (1)$$

In equation (1), the first term is associated to the accumulated sensible heat and the second term represents the heat flux due to the conduction, convection, radiation and others. In this equation, *m* represents the mass, *Cp* represents the specific heat, *T* represents the temperature, *t* represents the time and $\dot{Q}_i$ represents the heat flux. The system of energy balance equations is solved by the Runge Kutta Fehlberg method.

In the simulation, for each trunk, branch and leaf, three situations are considered, through a cylindrical composite wall:

- Central cylinder, which exchanges heat by conduction with the surrounding cylindrical shell;
- Cylindrical shell located between a cylindrical shell upstream and another cylindrical shell downstream; in this case, the cylindrical shell located between the other two exchanges heat by conduction with the cylindrical shell upstream and the cylindrical shell downstream;
- Cylindrical shell located between a cylindrical shell upstream and the external environment downstream; in this case, the cylindrical shell exchanges heat by conduction with the cylindrical shell upstream, by convection (natural, mixed and forced) with the outside environment and by radiation with the fire front and the surrounding environment.

3 NUMERICAL METHODOLOGY

The height of the virtual maritime pine tree is 7.5 m. It is constituted by 8863 cylindrical elements divided into 36 trunks, 97 branches and 8730 leaves. These elements are spread over four levels. The first level corresponds to the set of trunks, branches and leaves closest to the ground, while the fourth level corresponds to the set of trunks, branches and leaves located at the top of the maritime pine tree. Each maritime pine tree level is characterized by:

- Eight trunks and one vertical trunk section of the main trunk (Figure 1a);
- Each trunk has three branches, a total of 24 branches;

- Each branch has ninety leaves distributed by nine levels of ten leaves each (Figure 1b), a total of 2160 leaves;
- One branch and ninety leaves on the top of the higher level.

Table 1 shows the numbering of the elements of the virtual maritime pine tree for each level.

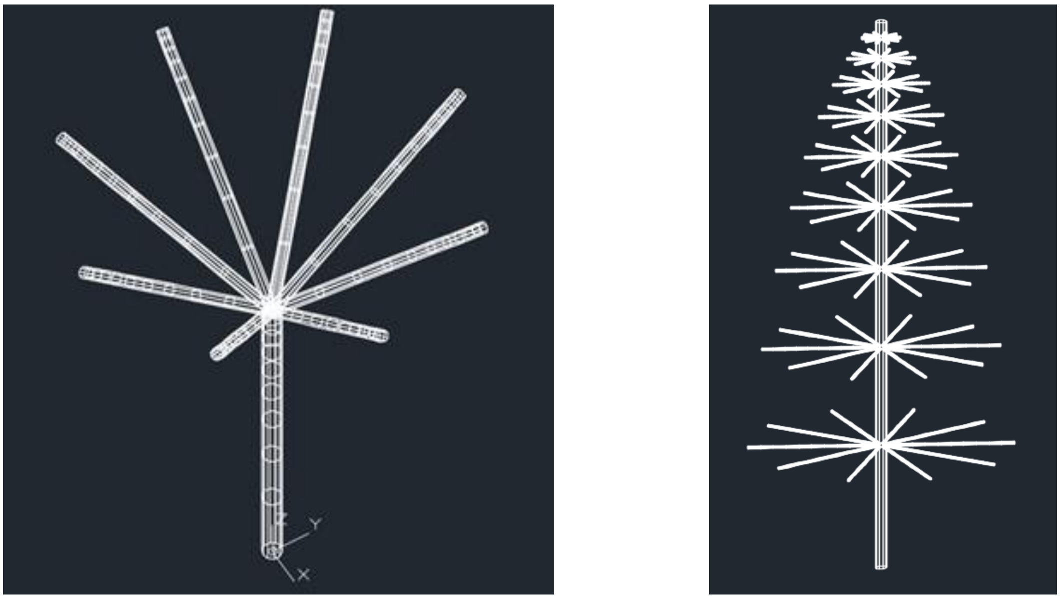
Table 1: Numbering the virtual maritime pine tree elements for each level

Level	Trunks/Branches	Leaves
1	1-34	134-2293
2	35-67	2294-4453
3	68-100	4454-6613
4	101-133	6614-8863

The dimensions of the fire front are 10 m long and 1 m high. The pine tree is placed perpendicular to the central area of the fire front and at a distance of 5 m (Figure 2). The fire front is considered static.

The input data of the numerical simulation are as follows: flame mean temperature, 500ºC; air temperature, 20ºC; air relative humidity, 50%; wind speed, 10 m/s.

The numerical simulation was performed in order to obtain as output data the view factors and the evolution of the surface temperature of the maritime pine tree elements in a transient regime. The evolution of the surface temperature was obtained for a time interval of 3600 seconds.



a) b)

Figure 1: Grid generation: a) between the main trunk and the secondary trunks; b) branch with leaves (pine needles)

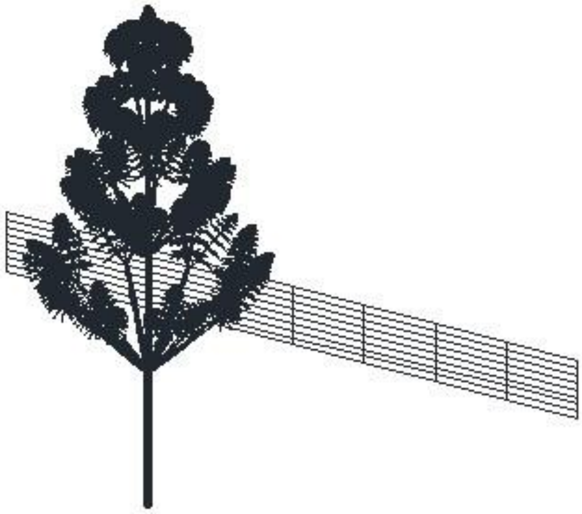


Figure 2: Grid generation on the tree and in the fire front

4 RESULTS AND DISCUSSION

In this section, the results obtained from the view factors (Figure 3) and the evolution of the surface temperature (Figures 4 to 7) of the maritime pine tree elements are presented and discussed. Figures 4 to 7 are associated, respectively, with levels 1 to 4 defined in the maritime pine tree. In these Figures, the results obtained in the branches with leaves facing the fire front are presented, that is, those most exposed to the fire. In these Figures, the elements referring to the leaves, the branch to which these leaves are attached and the trunk to which the branch is connected are also numerically identified.

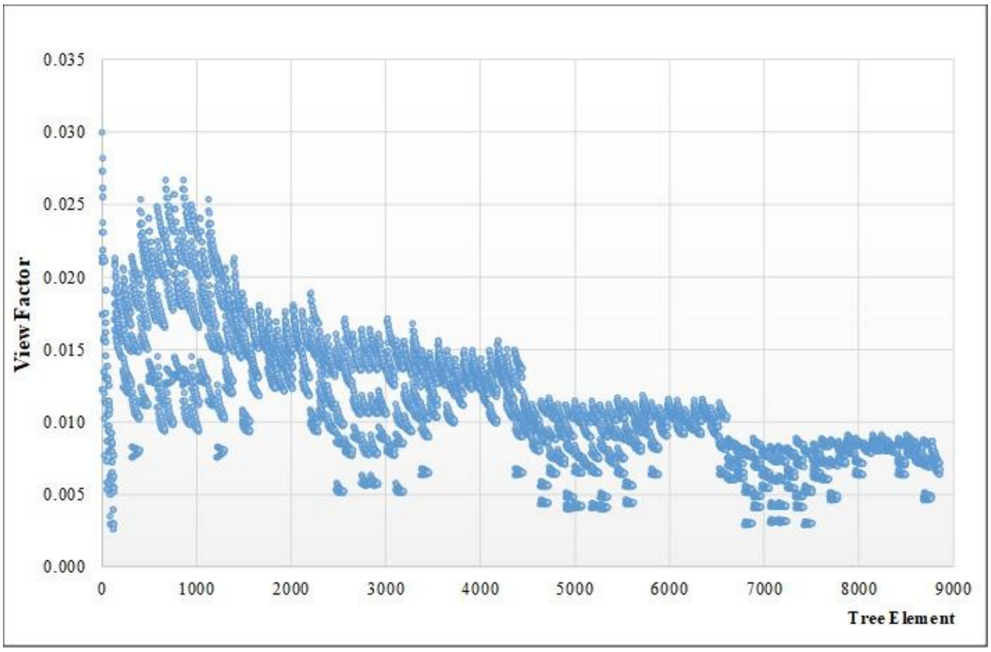


Figure 3: View factors of the maritime pine tree elements

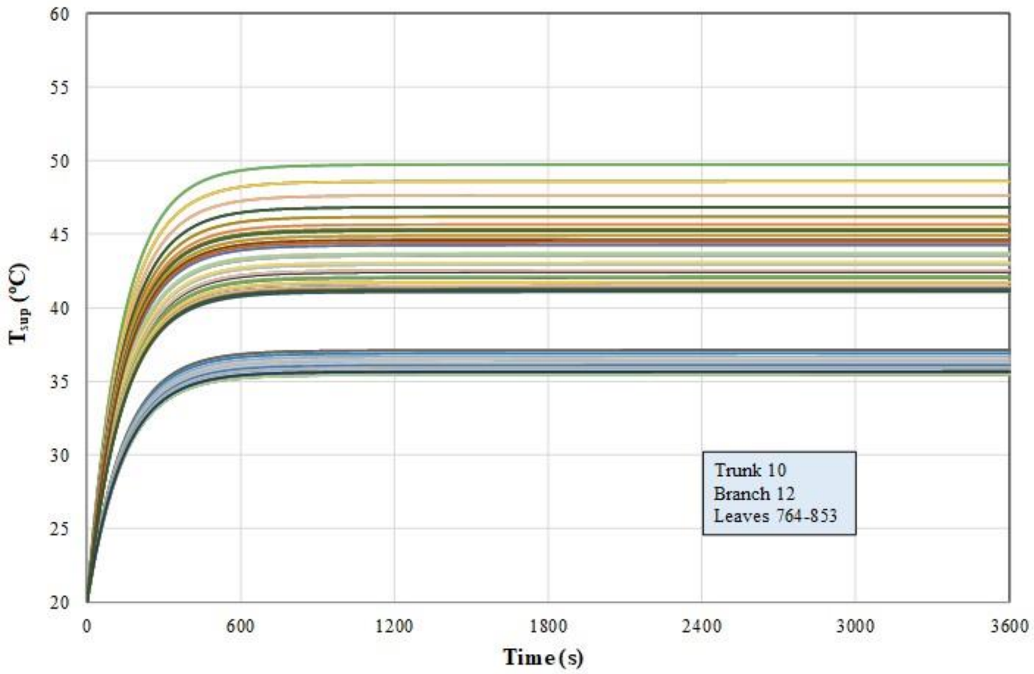


Figure 4: Evolution of the surface temperature of the leaves (elements 764-853) of the branch 12, located on level 1, facing towards the fire front

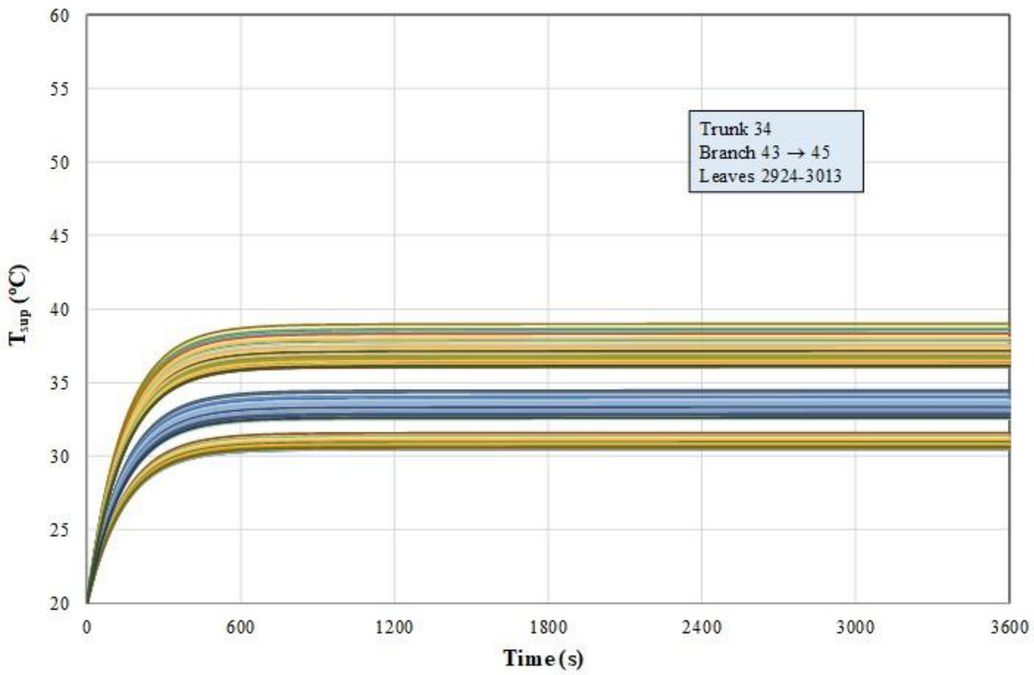


Figure 5: Evolution of the surface temperature of the leaves (elements 2924-3013) of the branch 45, located on level 2, facing towards the fire front

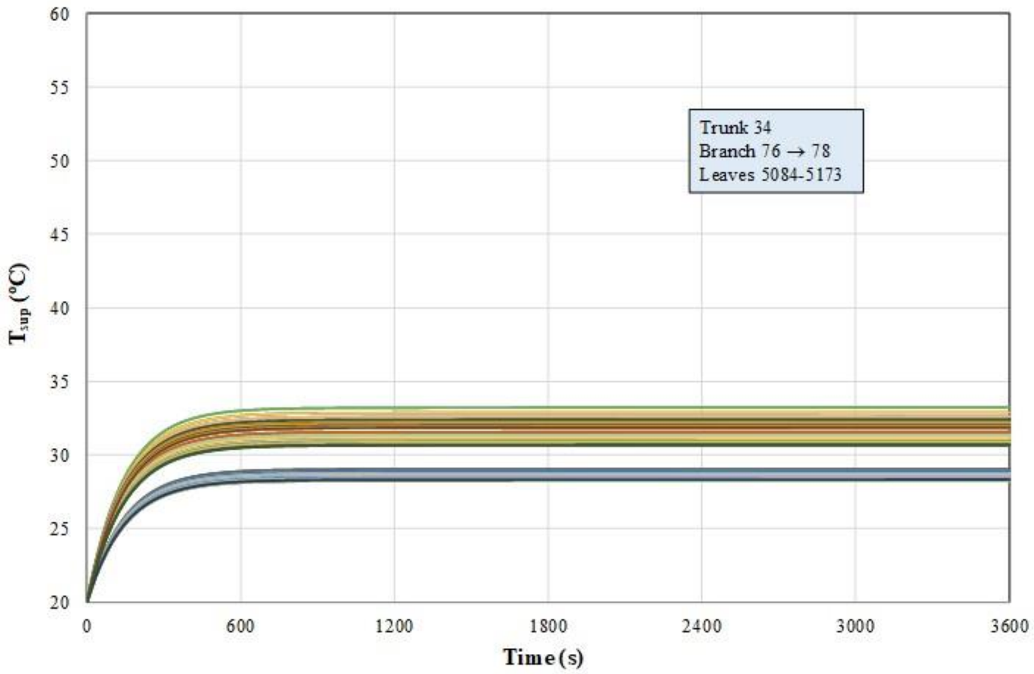


Figure 6: Evolution of the surface temperature of the leaves (elements 5084-5173) of the branch 78, located on level 3, facing towards the fire front

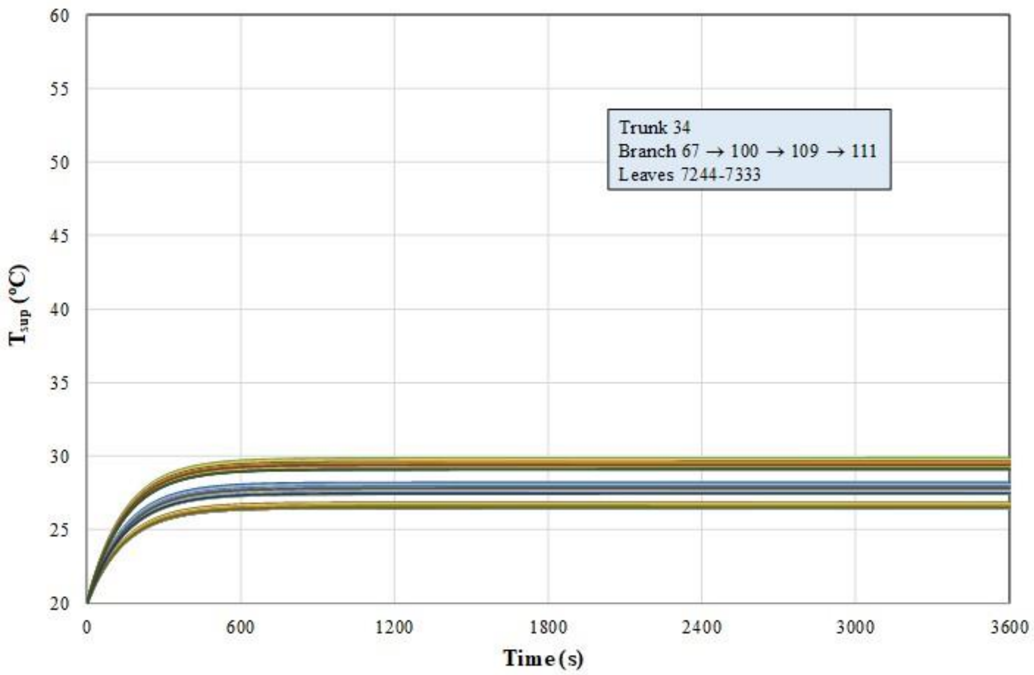


Figure 7: Evolution of the surface temperature of the leaves (elements 7244-7333) of the branch 111, located on level 4, facing towards the fire front

The values of the view factors obtained show that its maximum value is reached in the main trunk (element 1) and that its minimum value is reached in the branch, element 124, located at the top of the pine tree (level 4) in the opposite area to that of the fire front, that is, in the most protected area of the pine tree. With regard to leaves, the values of the view factors decrease from level 1 to level 4, that is, from the bottom to the top of the maritime pine tree. By level, the highest values are obtained on the leaves that are in the area of the pine tree facing the fire front and the lowest values are obtained on the leaves that are in the area of the pine tree opposite the fire front.

The surface temperature of the leaves decreases from level 1 to level 4. The surface temperature of the leaves varies between 35.7º and 49.7ºC in level 1, between 30.6º and 39.0ºC in level 2, between 28.3º and 33.2ºC in level 3, and between 26.5º and 29.6 ºC in level 4. It is noted that the distribution of surface temperatures is more uniform in the leaves of the branches at the top of the pine tree than in the leaves of the branches closest to the ground. By level, the surface temperature of the leaves located at the front of the branch are lower than those located at the rear. In each Figure, this is evidenced by the grouping of the surface temperatures of the leaves according to two or three sets of values. For example, the distribution of the surface temperatures of the leaves of level 2 can be defined according to three sets of values: one, between 30.1º and 31.3ºC; two, between 32.6º and 34.1ºC; and three, between 36.2º and 39.0ºC.

The surface temperature of the leaves settles after about 900 s for level 1, about 800 s for level 2, about 700 s for level 3 and about 600 s for level 4. The results show that surface temperatures stabilize more quickly on leaves located on the branches at the top of the tree than those located on branches closer to the ground.

In general, the results show that the elements of the pine tree (trunks, branches and leaves) present a different thermal behavior in front of a fire depending on their location in the pine tree. The most affected elements are those that are closest to the ground and that face the fire, as it is expected given the height of the fire front to be only 1 m.

5 CONCLUSIONS

In this work, the numerical model of the maritime pine tree thermal behaviour was developed from a grid generation geometry and energy balance integral equations that represent the heat transfer processes. It was applied in a situation where the pine tree is subject to the effect of a fire front with a height of 1 m and a flame temperature of 500ºC. The trunks, branches and leaves of the pine are represented by 8863 cylindrical elements and are arranged over four levels. The results of the numerical simulation were the view factors and the transient evolution of the surface temperature of the maritime pine tree elements.

The main conclusions are that the values of the form factors of the elements decrease from level 1 (lower zone) to level 4 (upper zone) of the pine tree. The surface temperature of the leaves decreases as the level of the pine tree rises. The distribution of surface temperature also becomes more uniform as the level of the pine tree rises. The stabilization of the surface temperature occurs in less time at the upper levels than at the lower levels. The leaves located in front of the branch (towards the fire front) have the highest values of surface temperature. Thus, it is noted that the thermal behaviour of the pine tree is not uniform and that it is possible to identify which areas are most affected in the presence of a forest fire.

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