TEMPERATURE EVOLUTION AND PROPAGATION OF DRYING, PYROLYSIS AND CHARRING FRONTS INSIDE WOOD SLABS AND CYLINDERS

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Abstract. *Determination of wood burning characteristics is important for fire safety engineering and due to the environmental and biogeochemical effects of forest fires. This work describes the temperature evolution and the velocities of the drying, pyrolysis and charring fronts in pinus wood (Pinus elliot) slabs and cylinders. Dry wood slabs (10×10×5* cm^3*) with different fiber orientations were tested in a conical calorimeter whereas wood cylinders (10 cm height, 3 cm diameter) with different moisture contents (0, 25 and 50 %, dry basis) were tested in a especially designed cylindrical calorimeter, all of them under a constant heater output.*

Keywords*: wood, pyrolysis, drying, charring, temperature*

1. INTRODUCTION

The capability to predict the burning rate of wood in modern times has become increasingly important as fire safety engineering moves toward a performance-based approach to building design (Spearpoint, 1999, 2001).

Combustion of biomass, mainly wood, releases pollutants in the atmosphere, increasing global warming, acid rain formation, production of smoke and particulates. It causes direct problems to the health of populations, worsen visibility conditions, produces ecological unbalance with reduction in biodiversity, damage the biogeochemical cycles and other adverse effects (Crutzen e Andreae, 1990).

Burning of wood presents several phases: pre-heating, drying, ignition, pyrolysis, flaming, flame extinction, smoldering and smoldering extinction. The flaming phase occurs when the volatiles from wood pyrolysis mix with air above the lean flammability limit in the boundary layer adjacent to the wood sample, and the gas temperature is above the ignition point (Kanury, 1977). Smoldering is a slow flameless heterogeneous burning process in which the residual char from pyrolysis is oxidized by air. Smoldering can last several days after fires, especially in the case of large logs or ground vegetation. Several of these phases can occur simultaneously, for example, drying and pyrolysis.

Many studies of different aspects of the burning of wood have been made. Abu-Zaid and Atreya (1989) studied the ignition of cellulosic materials and took into account the effect of moisture on in their studies. Suuberg, Milosavljevic and Lilly (1994) made a detailed analysis of pyrolysis kinetics of cellulose, which is the main component of wood. Saastamoinen and Richard (1996) made a numerical study of the simultaneous drying and pyrolysis of solid fuel particles. Di Blasi et al. (2003) investigated numerically and experimentally the drying of pinus cylinders in fixed bed under a heated counterflow air, to analyze drying conditions of wood in gasifiers/combustors. Galgano and Di Blasi (2004) modeled the propagation of drying and decomposition fronts in wood.

The role played by moisture transport phenomena is dependent on the heating conditions. In relatively low temperatures free water capillarity and diffusion of bound water play a controlling role, with liquid-phase flows two or three orders of magnitude larger than the vapor fluxes. The high-temperature behavior has been simulated by Di Blasi et al. (2003) by considering the propagation of an evaporation front during the entire duration of the process together with significant gas phase convective transport. In general, the presence of moisture introduces a delay in the heating time, with consequent variations in reaction temperatures, product distribution and ignition times.

The effects of moisture, diameter and heat input on burning characteristics of wood cylinders of several Brazilian species have been studied experimentally by Castro (2005) and Castro and Costa (2005a,b) using a cylindrical calorimeter. A theoretical model of burning of wood cylinders was presented by Costa et al. (2003) and a numerical model to describe the combustion process of wood cylinders was developed by Costa and Castro (2005).

Costa and Castro (2006a,b) determined and compared combustion characteristics of pinus wood (*Pinus elliot*) slabs burned inside a conical calorimeter, considering the effects of wood fiber orientation on burning. The mass evolution, consumption rate, characteristic times (ignition, pyrolysis and charring) and emissions (CO, CO_2, NO, UHC) of pinus slabs with fibers parallel and perpendicular to the heating surface were measured.

However, despite the large amount of literature on wood burning, there is still a limited amount of data related to the drying, pyrolysis and burning processes of tropical woods under controlled conditions. Thus, the objective of this work is to present the temperature evolution and the average propagation velocities of the drying, pyrolysis and charring fronts inside cylinders and slabs of pinus wood (*Pinus elliot*), a common softwood in Brazil, heated and burned within conical and cylindrical calorimeters, respectively.

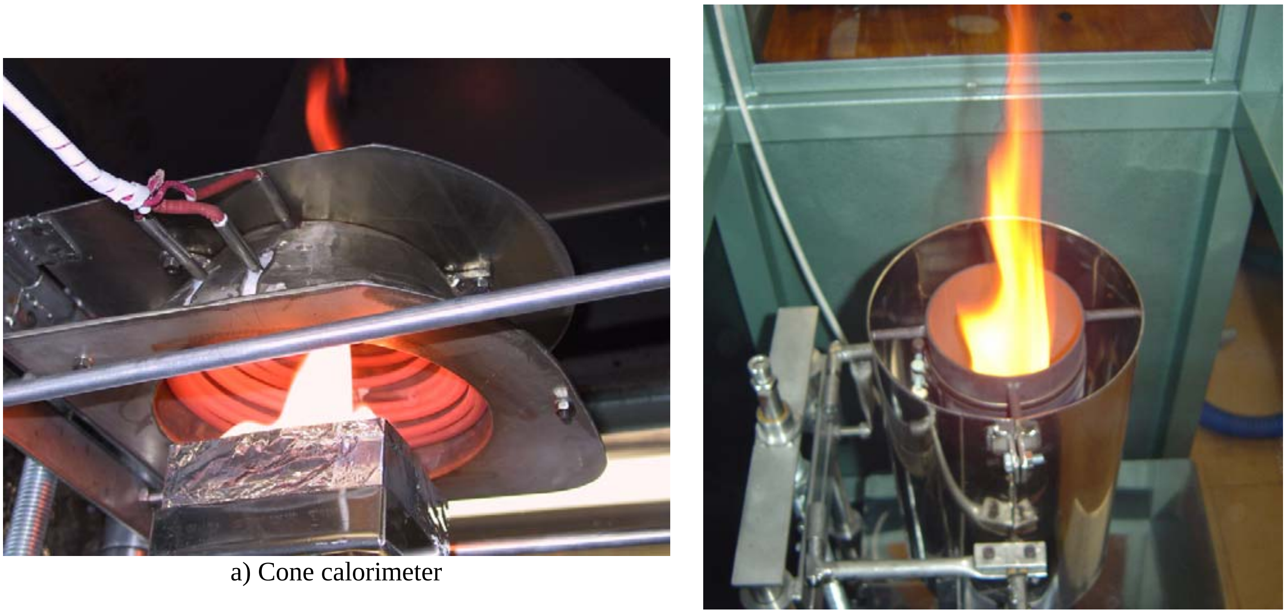
Results of the present work can be employed in the validation of numerical codes, assessment of fire risks, related studies of fire prevention and simulation of forest fires and fires, in general.

2. METHODOLOGY

A cylindrical calorimeter, with a maximum power output of 2000 W, was designed and built for heating and burning cylinders of solid materials, including cellulosic materials and polymers.

A cone calorimeter, with a maximum power output of 5000 W, was built based on the ASTM E1354–03 standard, for heating and burning slabs of solid materials. Figure 1a depicts the cone calorimeter and Fig. 1b shows the cylindrical calorimeter, both with samples burning.

A detailed description of the calorimeters and test workbench used in this study, including sampling, power control and data acquisition systems, is made by Castro (2005).



a) Cone calorimeter

b) Cylindrical calorimeter

Figure 1. Calorimeters used for heating and burning the slabs and cylinders.

2.1. Sample preparation

Wood samples were obtained from pinus trees (*Pinus elliot*), recently cut. The logs were cut in 30 cm dowells, which were packed and frozen until machining. Freezing reduced moisture losses and wood deterioration, thus yielding good machining conditions. The samples were machined as slabs (10×10×5 cm^3) and cylinders (10 cm height and 3cm diameter). After machining, the slabs and cylinders were packed and frozen again.

Before test, the slabs were oven dried during 24 h, at 103 ^oC, since tests were made at a 600 m altitude. At the sea level the standard temperature is usually 105 ^oC. It was assumed that only moisture is released from wood at this temperature. After dried, the cylinders were placed in a pressurized water chamber (1.5 atm) until reach the required moisture content. Two cylinders with a given moisture content (0 %, 25 % and 50 %, dry basis) were prepared and kept frozen until 24 hr before test, when they were unfrozen at room temperature.

More details on sample preparation can be found in Castro (2005).

2.2. Temperature measurements

In order to measure the temperatures in the samples, 9 thermocouples (K-type) were placed in different positions inside the wood slabs and cylinders. The samples were heated and burned under a constant heat output of 2000 W in both conical and cylindrical calorimeters.

The thermocouples in the cylindrical samples were placed in the center, at 5 mm radius and 10 mm radius, and at 30, 50 and 70 mm height, using 3 thermocouples at each height and 3 thermocouples at each radial position. In the slabs, the thermocouples were placed at 30 mm from the vertical edges of the samples and at 10, 20 and 30 mm depths, measured from the exposed surface, with 3 thermocouples per depth. Figures 2 and 3 show pictures of the configurations adopted for positioning the thermocouples inside the cylinders and slabs, respectively.

Figure 2. Configuration of thermocouples inside the cylinders.

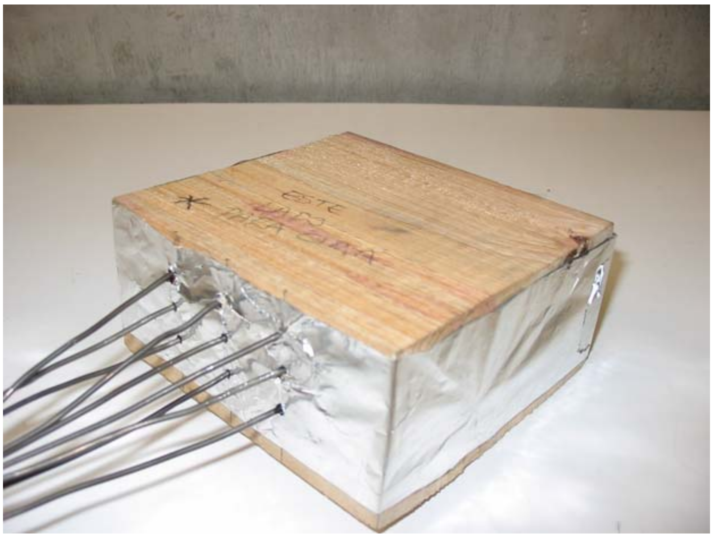


Figure 3. Configuration of thermocouples inside the slabs.

3. RESULTS AND DISCUSSION

Figures 3 and 4 show the temperature evolution inside pinus wood cylinders with 0 % moisture content. Figures 5 and 6 show the temperature evolution inside pinus wood cylinders with 25 % moisture content. Figures 7 and 8 show the temperature evolution inside pinus wood cylinders with 50 % moisture content.

Figures 9 and 10 present the temperature evolution inside pinus wood slabs with 0 % moisture content and wood fibers parallel to the exposed surface. Figures 11 and 12 present the temperature evolution inside pinus wood slabs with 0 % moisture content and wood fibers perpendicular to the exposed surface.

In some cases there are oscillations in the measured temperatures which can have several causes, such as cracking in the wood or char structure, nearby resin inclusions, displacement of thermocouples and an intermittent flow of volatiles.

In the wood cylinders there occurs a clear change in the curvature of the temperature profiles caused by the ignition process, when there is an increase in the temperature growth and an increase in the pyrolysis rate, caused by the higher heating produced by the flame.

At about 400 s, for dry cylinders, the temperature curves meet and stabilize in a plateau between 700 and 800 ºC. This moment indicates that the smoldering region has reached all thermocouples. With this information it is possible to calculate the charring front velocity of the sample, by registering the position and time required for a thermocouple to attain a temperature from 700 to 800 ºC, the average smoldering temperature; the confluence of the curves facilitates the location of the point where the smoldering front passes. The pyrolysis front velocity also can be calculated by registering the time when a thermocouple attains an average pyrolysis temperature, about 300 ºC. To calculate the drying front velocity, the same procedure is adopted, but considering a fixed drying temperature of 100 ºC.

In the cylinders with higher moisture content there is a displacement of the inflection points which indicate the pyrolysis regimes and there is an earlier point indicating the passage of the drying front (100 ºC). There is also a plateau during the smoldering phase, and there is no significant change of smoldering temperature (about 800 ºC) with change in moisture content. The presence of moisture delays the temperature rise up to attain the smoldering phase and smooths out the temperature curves during pyrolysis.

There are differences in the temperature curves during smoldering among the dry samples and the samples with the larger moisture content, 50 %. For dry samples the smoldering temperatures are approximately constant, whereas for samples with moisture content of 50 % the smoldering temperature curves follow, approximately, a parabolic profile. This difference can be explained by the presence of two smoldering regimes: smoldering with reaction inside the char pores and combustion only at the char surface, as explained by Kanury (1994). The occurrence of surface combustion or combustion inside the pores depends on the heterogeneous char oxidation rate and depends on the diffusion rate of oxygen inside the pores. The heterogeneous reaction rate depends on char composition and the oxygen diffusion depends on geometry and distribution of pores. Both depend on the temperatures and pressure inside the pores.

The dry slabs have behavior similar to the dry cylinders, however with a larger time scale. Despite being ovendried the slabs exhibit the passage of a drying front, as seen by the curvature change about 100 °C, because there is residual moisture within the wood cells or cell walls.

Table 1 shows the average velocities of the drying, pyrolysis and charring fronts inside the pinus samples, determined by temperatures of water vaporization, pyrolysis and smoldering, respectively, measured by the thermocouples. All cylinders and slabs tested were ignited. It can be seen in Table 1 that front velocities present a significant decrease with increasing moisture contents. The front velocities of dry cylinders are much larger than front velocities of the dry slabs. There is no significant effect of fiber orientation of slabs on front velocities.

Table 1. Average values of velocities of the drying, pyrolysis and charring fronts, in cylinders and slabs of pinus wood (*Pinus elliot*).

Sample	**Drying front velocity (mm/s)**	**Pyrolysis front velocity (mm/s)**	**Charring front velocity (mm/s)**
Cylinder – 0% H_2O	0.2225	0.070512	0.021754
Cylinder – 25% H_2O	0.1558	0.045095	0.015443
Cylinder – 50% H_2O	0.0605	0.020913	0.010402
Slab with fibers parallel to the exposed surface, with flaming	0.0829	0.029245	0.006902
Slab with fibers perpendicular to the exposed surface, without flaming	0.0870	0.022031	0.005429
Slab with fibers perpendicular to the exposed surface, with flaming	0.0805	0.022750	0.005178

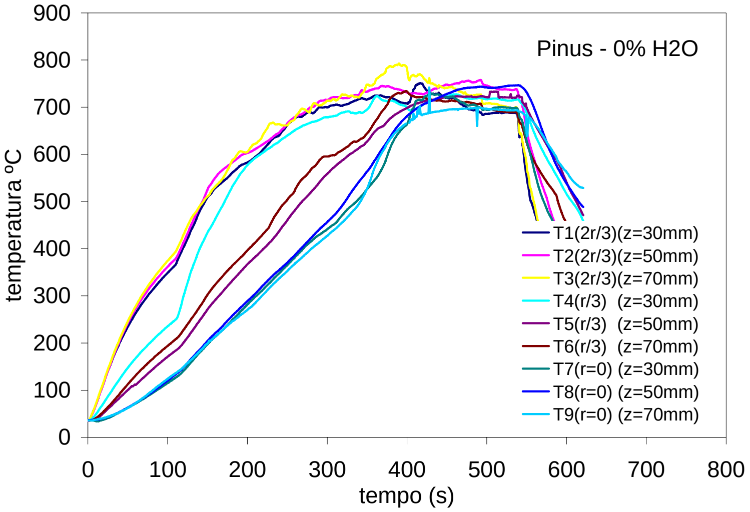


Figure 4. Temperature evolution inside a pinus wood cylinder with 0 % moisture content.

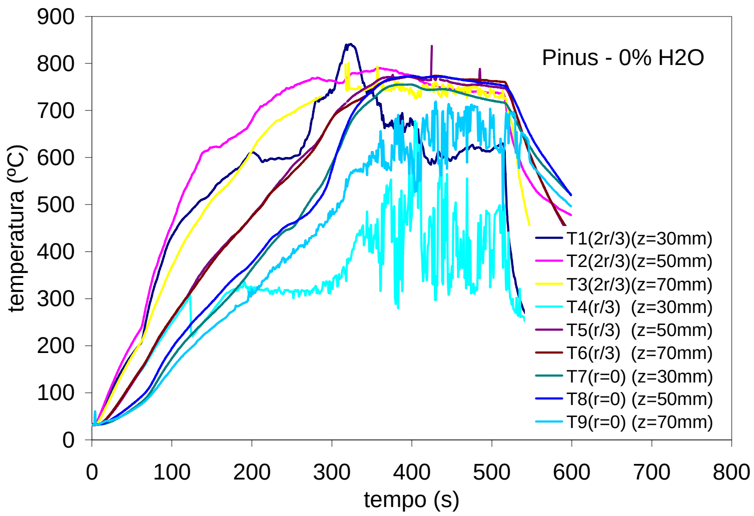


Figure 5. Temperature evolution inside a pinus wood cylinder with 0 % moisture content.

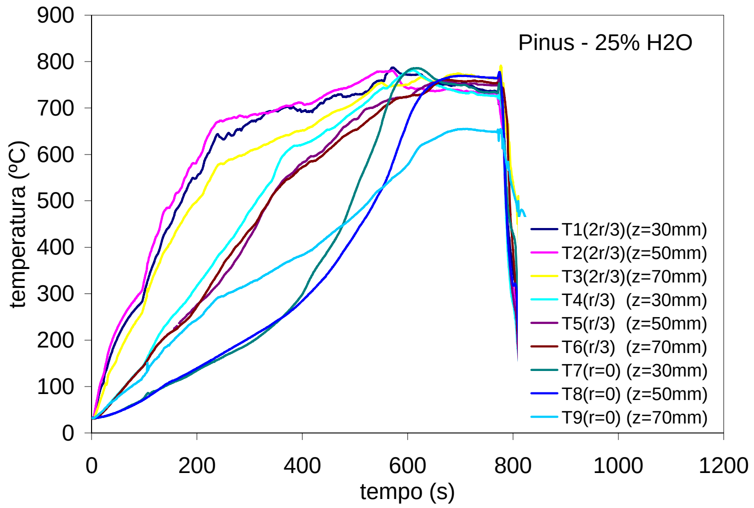


Figure 6. Temperature evolution inside a pinus wood cylinder with 25 % moisture content.

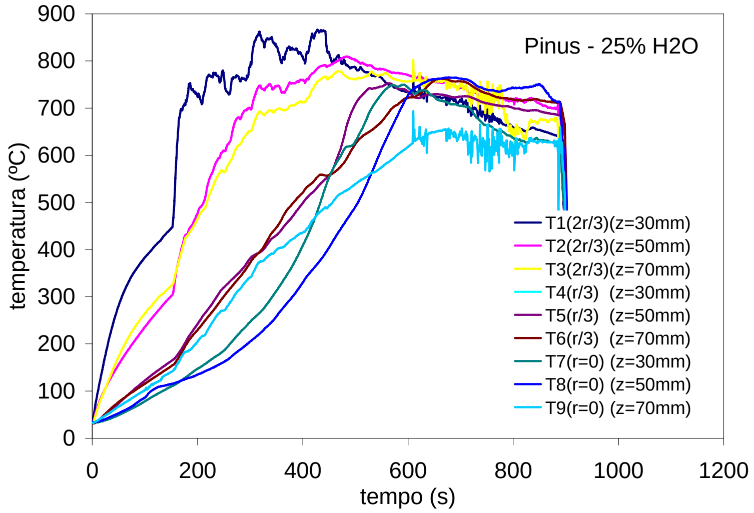


Figure 7. Temperature evolution inside a pinus wood cylinder with 25 % moisture content.

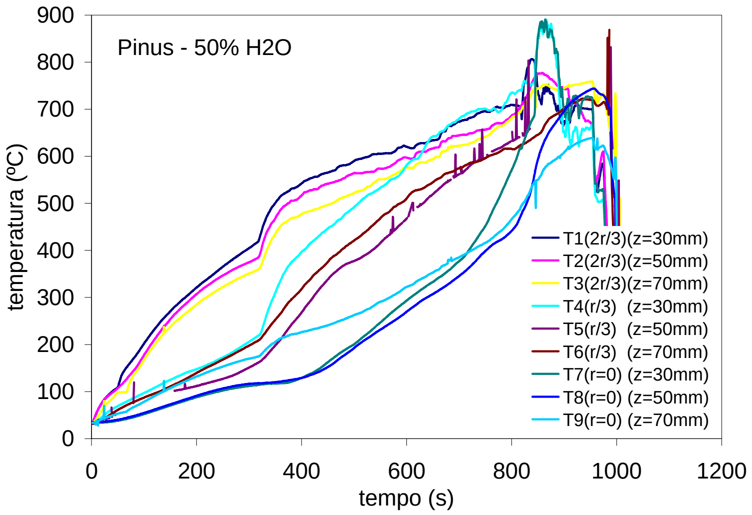


Figure 8. Temperature evolution inside a pinus wood cylinder with 50% moisture content.

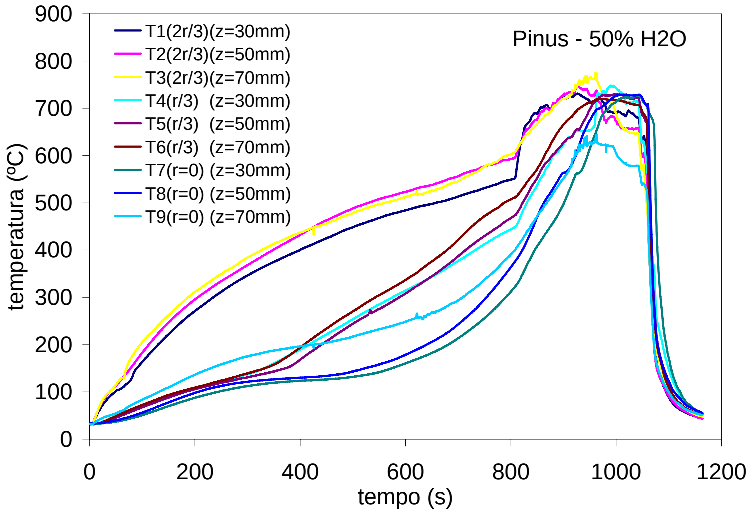


Figure 9. Temperature evolution inside a pinus wood cylinder with 50% moisture content.

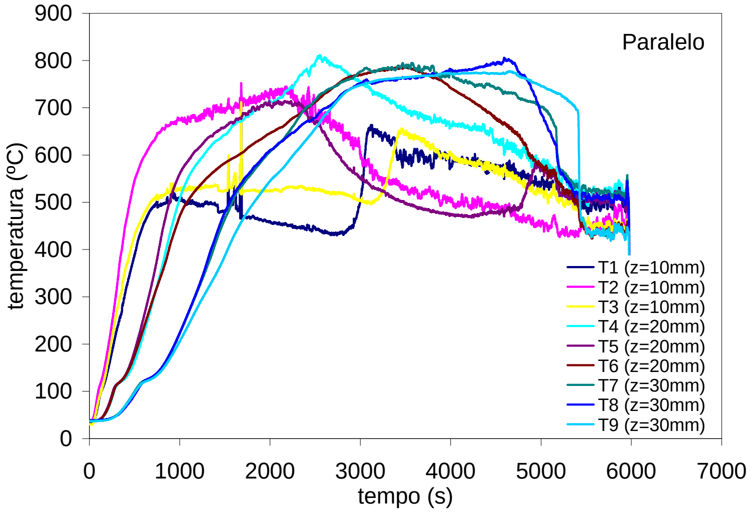


Figure 10. Temperature evolution inside a pinus wood slab with fibers parallel to the exposed surface.

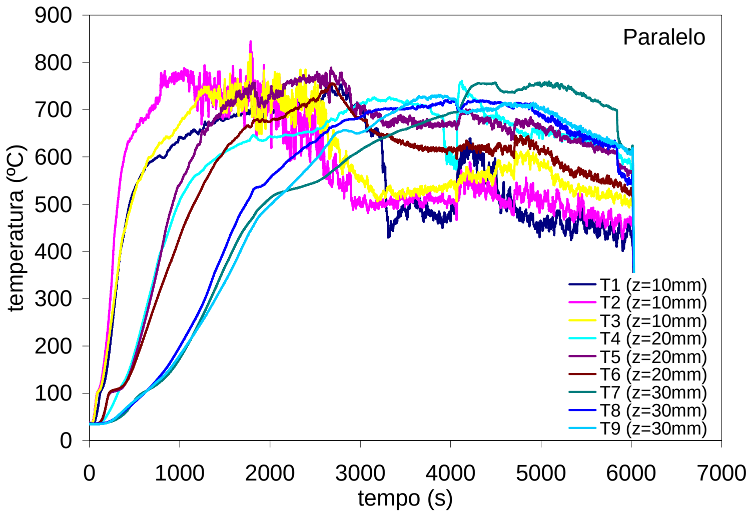


Figure 11. Temperature evolution inside a pinus wood slab with fibers parallel to the exposed surface.

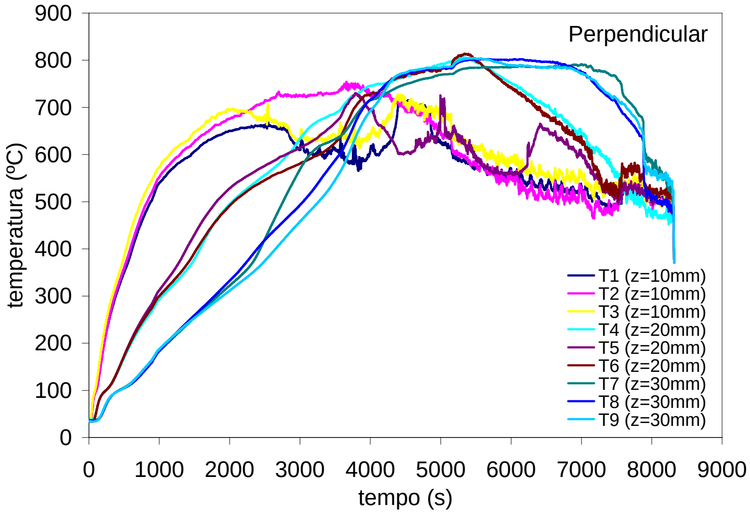


Figure 12 – Temperature evolution inside a pinus wood slab with fibers perpendicular to the exposed surface.

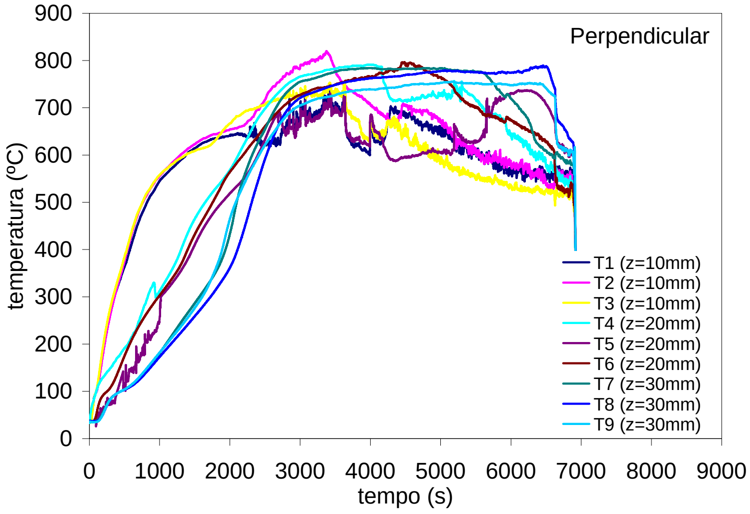


Figure 13 – Temperature evolution inside a pinus wood slab with fibers perpendicular to the exposed surface.

4. CONCLUSIONS

The temperature evolution inside cylinders and slabs of pinus wood (*Pinus elliot*) heated and burned in cone and cylindrical calorimeters was measured by thermocouples. The average propagation velocities of drying, pyrolysis and charring fronts were calculated. It was verified a significant decrease on reaction rates in wood cylinders caused by increasing moisture content. Fiber orientation had no significant effect on reaction rates of wood slabs. Ignition determined an increase on temperature rates and pyrolysis rates, caused by flame heating. Wood heterogeneities caused differences in ignition times, thus affecting significantly the temperature curves. Smoldering temperatures were approximately constant, about 700-800 ^{o}C.

5. ACKNOWLEDGEMENTS

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