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BURNING OF WOOD SLABS IN A CONICAL CALORIMETER. PART I: CONSUMPTION RATES AND CHARACTERISTIC TIMES

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Abstract. *This work presents experimental data concerning the combustion characteristics of wood slabs of pinus (Pinus elliot) burned in a conical calorimeter. The mass evolution, normalized mass evolution, consumption rates, percent consumption rates, times of self-ignition, pyrolysis and flaming of square slabs (10x10x5cm^3) were obtained for a constant heat output of 2000 W. The behaviours of slabs with fibers parallel or perpendicular to the heating surface are compared during pre-heating, drying, self-ignition, pyrolysis, flaming, flame extinction and smoldering.*

Keywords. Combustion, self-ignition, pyrolysis, smoldering, conical calorimeter, slab

1. Introduction

Ever since prehistoric times humans have known that wood burns and the ability of wood to burn has been both a benefit and a problem. 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 and Andreae, 1990).

Combustion of biomass 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 the burning phases can occur simultaneously in several conditions, for example, drying and pyrolysis in the high temperature zones of fixed-bed concurrent and fluid-bed gasifiers/combustors.

Many studies of different aspects of the burning of wood have been made. Abu-Zaid and Atreya (1989) took into account the effect of moisture on the ignition of cellulosic materials in their studies. Suuberg, Milosavljevic and Lilly (1994) made a detailed analysis of pyrolysis kinetics of cellulose, 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. Di Blasi er al. (2003) simulated 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 (Di Blasi et al., 2003).

Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen. Pyrolysis is also a common technique to produce liquids from solid biomass. The most common technique uses very low residence times (< 2 s) and high heating rates using a temperature between 350-500 °C and is called either fast or flash pyrolysis. The production of charcoal through the pyrolysis of wood has been widely used. In many industrial applications the process is done under pressure and at operating temperatures above 430°C.

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 simplified numerical model to describe the combustion process of wood cylinders was developed by Costa and Castro (2005).

There is still a limited amount of data in literature related to the drying, pyrolysis and burning processes of Brazilian woods under controlled conditions. The previous studies made by Costa and Castro focused on combustion characteristics of wood cylinders with the same wood fiber orientation, i.e., parallel to the heating surface.

Therefore, the objective of this work is to determine and compare combustion characteristics of pinus wood (*Pinus elliot*) slabs burned inside a conical calorimeter, considering the effects of wood fiber orientation on burning. Samples with fibers parallel and perpendicular to the heating surface are tested.

In this paper data are presented concerning mass evolution, mass consumption rates, normalized mass evolution, percent consumption rates, self-ignition times, end of pyrolysis times, flaming times, of ovendry square wood slabs with exposed area of 10x10 cm^2 and 5 cm thickness.

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

2. Experimental Setup

The tests and the methodology of testing in a cone calorimeter are established by the ASTM E1354–03 "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter".

The objective of ASTM E1354–03 standard is to measure the response of materials exposed to controlled levels of radiating heat, with or without an external igniter. The test is used to determine the ignitability, heat release rates, mass consumption rates, effective heat of combustion and the release of visible smoke of materials and products.

A cone calorimeter, with a maximum heater output of 5000 W, was built based on the ASTM E1354–03 standard. Figure 1 depicts the cone calorimeter and Fig. 2 shows the test workbench.

A support was positioned below the heater system and placed on a digital scale, which had a 0.005 g precision and stabilization time less than 2 s. The heater was turned on by a temperature PID controller connected to a thermocouple positioned below the heater, outside the flame zone.

A data acquisition system and a continuous gas analyzer were used to register the instantaneous masses and emissions of CO, CO_2 and NO, the O_2 concentrations and temperatures.

The gases generated by the combustions process were removed by a radial fan to avoid smoke accumulation inside the hood above the calorimeter. The sampling of gases was made by a collection ring with twenty holes symmetrically distributed. A K-thermocouple registered the exhaustion temperatures of the gas samples. A detailed description of the cone calorimeter is given by Castro (2005).

3. Sample Preparation

Wood samples were obtained from pinus (*Pinus elliot*) trees, 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 (10x10x5 cm^3) and, after machining, the slabs were packed and frozen again.

Due to density variations in the samples, 24 dry slabs were selected with standard deviation less than 5 %. Dry slabs were used in order to reduce the mass dispersion and to assure more similar physical properties among the samples.

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.

Six ovendry square slabs with total dry mass similar were chosen for measuring mass evolution and consumption rates in the cone calorimeter: 3 slabs with exposed surface parallel to the wood fibers and 3 slabs with exposed surface perpendicular to the wood fibers.

4. Test procedure

Initially the heater system and the sample support were aligned vertically on the scale and the computer was connected to the scale serial output and turned on. The heat output was set at 2000 W by a PID controller. The heater was turned on until the air flow to reach a steady temperature, measured by a thermocouple below the heater. This temperature remained approximately constant until the flaming period, when it raised to 700-850 ºC, depending on the sample characteristics. During the smoldering phase the measured air flow temperatures were about 550 ºC.

The samples were unfrozen 24 hr before the test and then ovendried. After their masses were verified, they were placed on the sample support, below the cone heater. Thus, the scale registered the instantaneous mass of the sample at intervals of 1s during about 25 min, with a constant heat output from the heater.

The data acquisition system was started just after the sample was placed on the sample support.

Radiation heating and burning convected the hot air upward and brought cold air from the ambient into the heater.

Figure (3) shows photos of burning of pinus slabs in the cone calorimeter.

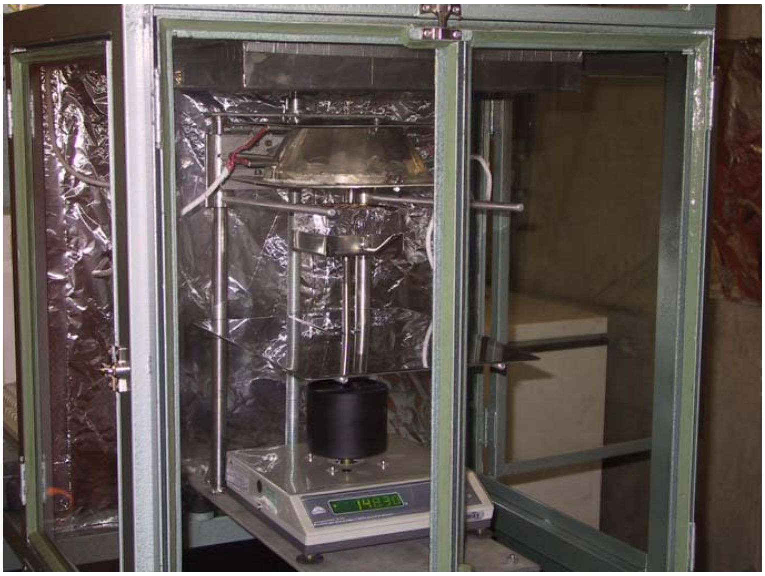

Figure 1 - Cone calorimeter.

Figure 2 - Experimental workbench.

5. Results

Figures 4 and 5 present the mass evolution, Figs. 6 and 7 present the normalized masses, Figs. 8 and 9 present the consumption rates, and Figs. 10 and 11 present the percent consumption rates of oven dry pinus slabs for heated surfaces parallel or perpendicular to the wood fibers. In these figures m is the instantaneous mass, m_o is the initial mass, m/m_o is the normalized mass, dm/dt is the consumption rate, and $(-100/m)dm/dt$ is the percent consumption rate of a slab. t is the heating time of the slab in the calorimeter. Data were selected at 10 s intervals, reducing scale stabilization effects.

It can be seen in Figs. 4-7 that the curves of mass evolution and normalized masses present points with a significant curvature change. In these tests all slabs self-ignited. If ignition occurs, the points with a change of curvature indicate the self-ignition and the flame extinction moments. In case of no ignition, they indicate the pyrolysis start, the end of pyrolysis and the change of the pyrolysis regime, with modification of the pyrolysis rate. After flame extinction or, in case of no flaming, after the end of pyrolysis, the smoldering process begins.

The points of start, end of pyrolysis and change of the pyrolysis regime change are identified more clearly observing the spikes and curvature changes in the curves of consumption rates and in the curves of percent mass consumption rates. Even when there is no self-ignition these curves present spikes, and the start of the pyrolysis process can be identified by the end of the initial increase in the consumption rates. The end of the pyrolysis process can be identified by the beginning of the region with a low and approximately constant consumption rate, indicating the existence of a smoldering process. In the region between ignition and flame extinction, the curves of consumption rates have, approximately, a parabolic profile for samples with heated surfaces perpendicular to the wood fibers and approximately semi-parabolic for the samples with heated surfaces parallel to the wood fibers.

The curves of mass evolution present low dispersion for slabs with heated surfaces parallel to the wood fibers, differently from the slabs with exposed surfaces perpendicular to the fibers. The normalized mass curves also follow this tendence. The consumption rate curves and the percent consumption rate curves present a larger dispersion, due to the presence or not of flaming and the different self-ignition times. It is verified that the wood fiber orientation affects the release rate of volatiles, which is larger, during pyrolysis, for samples with parallel fibers. Such observation can be associated to the different thermal conductivities of wood with respect to fiber's orientation. Thermal conductivity in the fiber direction can be two times larger than the thermal conductivity in a direction perpendicular to the fibers. In samples with fibers oriented parallel to the heating surface the thermal conductivity is lower, and the release rate of volatiles is larger due to the higher temperature, caused by the lower heat diffusion towards the cold bottom of the slab.

The curves of percent mass consumption rate present oscillations during smoldering, due to the lower masses at that phase and scale stabilization and delay time. Moving averages could be taken from the mass evolution data in order to determine an average profile without oscillations in the smoldering phase.

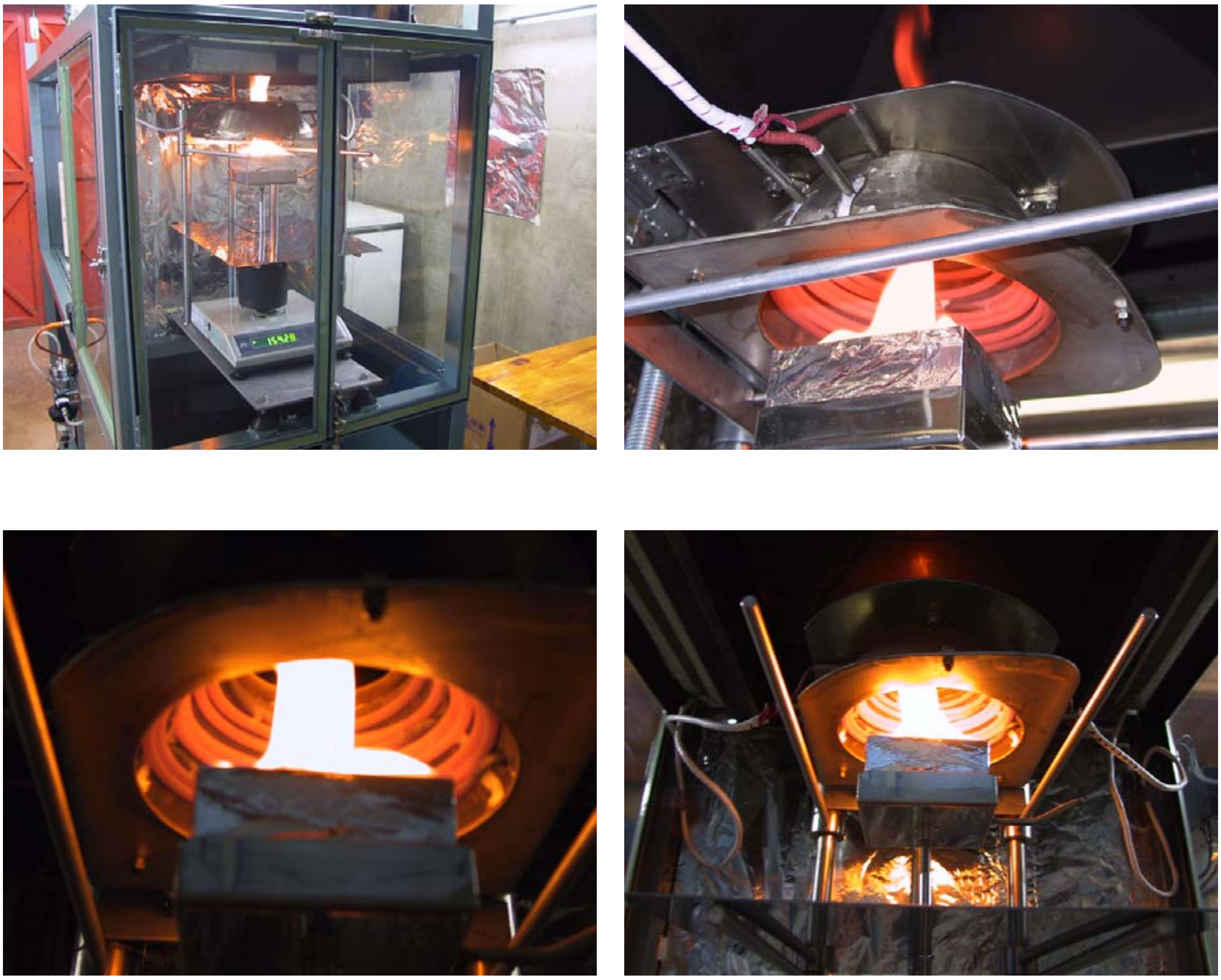

Figure 2 – Burning of pinus slabs in the cone calorimeter.

It is verified on Table 1 that the char fraction at end of pyrolysis and smoldering rates are not significantly affected by the orientation of the fibers. Pyrolysis rates were about 10 % larger for slabs with fibers parallel to the exposed surface than for fibers perpendicular to the exposed surface. Slabs C and F had ignition times much larger than the other slabs with the same fiber directions, probably due to physical and chemical heterogeneities inside the log from where the slabs were obtained. The average time of end of pyrolysis (flame extinction) for parallel orientation is about 2550 s, while for perpendicular orientation is about 2900 s, approximately 350 s larger, however the pyrolysis time is about the same for slabs parallel or perpendicular 2 and 3.

Additional data concerning CO, CO_2, UHC and NO emissions, oxygen consumption and exhaustion temperatures for the samples presented in this paper are given by Costa and Castro (2006).

Table 1 presents comparative data of the slabs with heating surfaces parallel and perpendicular to the wood fibers.

Table 1 – Slab data with different fiber orientations.

Fiber orientation	m_o (g)	t_{ig} (s)	t_{ep} (s)	Δt_p (s)	m_{ig} (g)	m_{ep} (g)	Δm_p (g)	dm_p/dt (g/s)	m_{ep}/m_o (%)	m_c (g)	dm_c/dt (g/s)
Parallel 1	173,57	700	2550	1850	128,52	41,40	87,12	0,0471	23,85	26,51	0,0090
Parallel 2	180,58	55	2560	2505	177,40	39,80	137,60	0,0549	22,04	19,62	0,0110
Parallel 3	184,45	22	2540	2518	183,30	40,90	142,40	0,0566	22,17	23,75	0,0090
Perpendicular 1	182,35	2061	3155	1094	85,94	41,33	44,61	0,0408	22,67	30,33	0,0100
Perpendicular 2	178,60	57	2650	2593	176,00	36,76	139,24	0,0537	20,58	20,45	0,0100
Perpendicular 3	180,37	390	2850	2460	156,00	44,83	111,17	0,0452	24,85	31,83	0,0090

m_o = initial mass, t_{ig} = ignition time, t_{ep} = end of pyrolysis time, Δt_p = pyrolysis time,
m_{ep} = mass at end of pyrolysis, Δm_p = pyrolysed mass, dm_p/dt = pyrolysys rate, m_{ep}/m_o = char fraction,
m_c = char mass at t = 4000 s, dm_c/dt = smoldering rate at t = 4000 s.

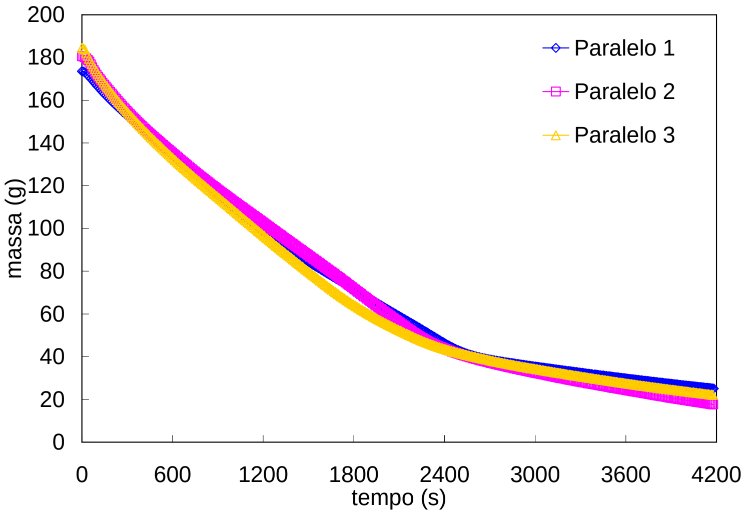

Figure 4 – Mass evolution of pinus wood slabs with heated surface parallel to the wood fibers.

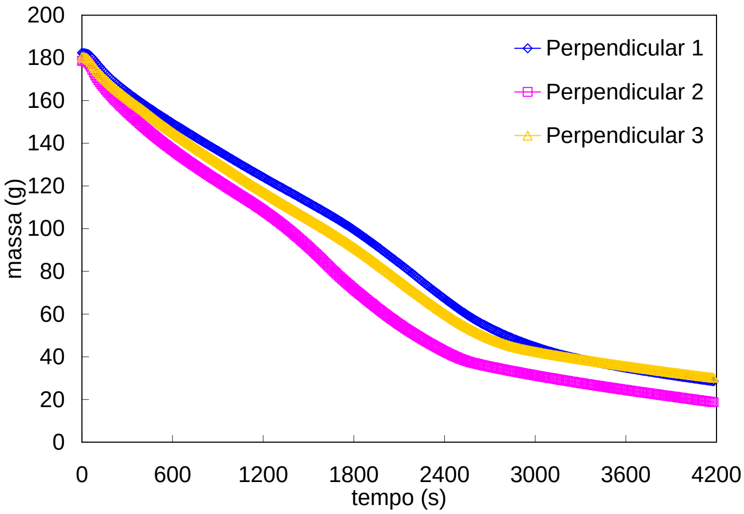

Figure 5 – Mass evolution of pinus wood slabs with heated surface perpendicular to the wood fibers.

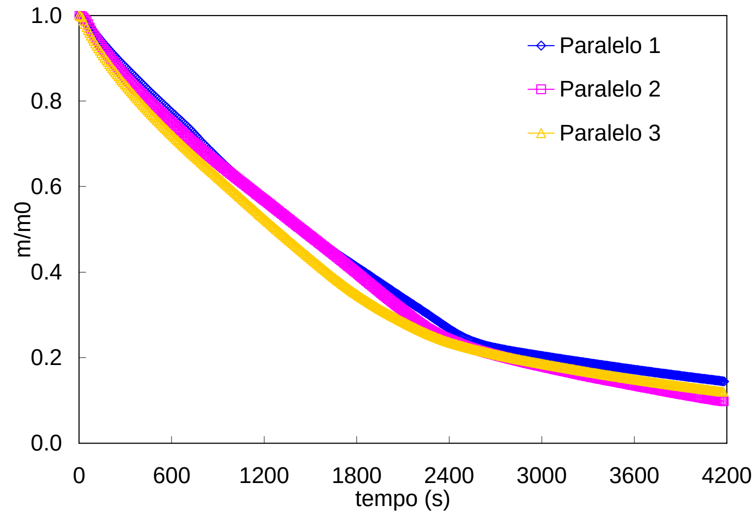

Figure 6 – Normalized mass evolution of pinus wood slabs with heated surface parallel to the wood fibers.

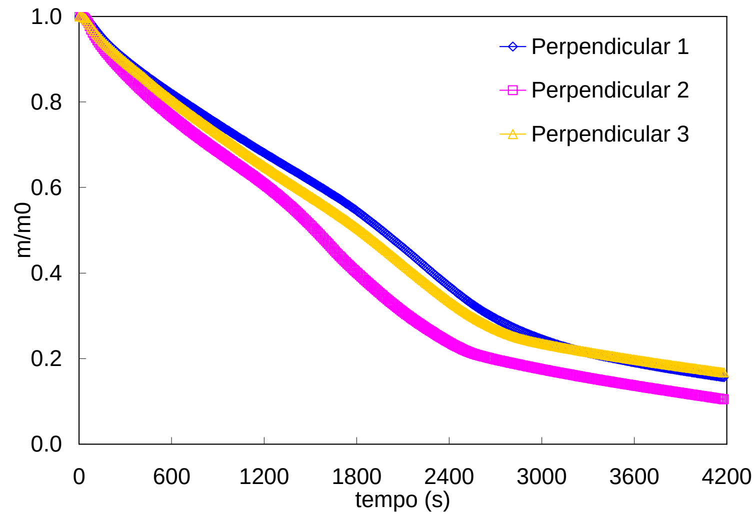

Figure 7 – Normalized mass evolution of pinus wood slabs with the heated surface parallel to the wood fibers.

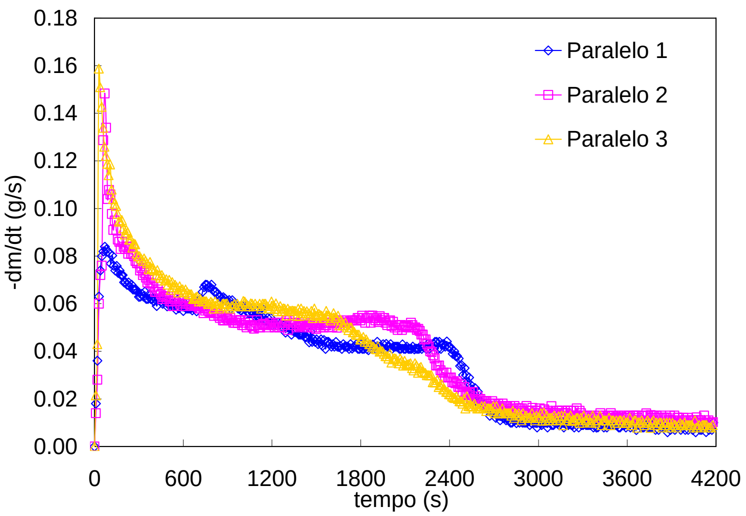

Figure 8 – Mass consumption rates of pinus wood slabs with the heated surface parallel to the wood fibers.

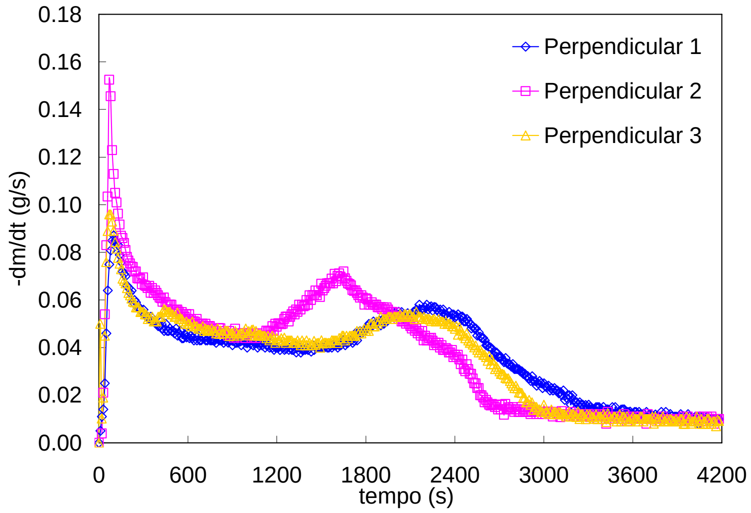

Figure 9 – Mass consumption rates of pinus wood slabs with the heated surface perpendicular to the wood fibers.

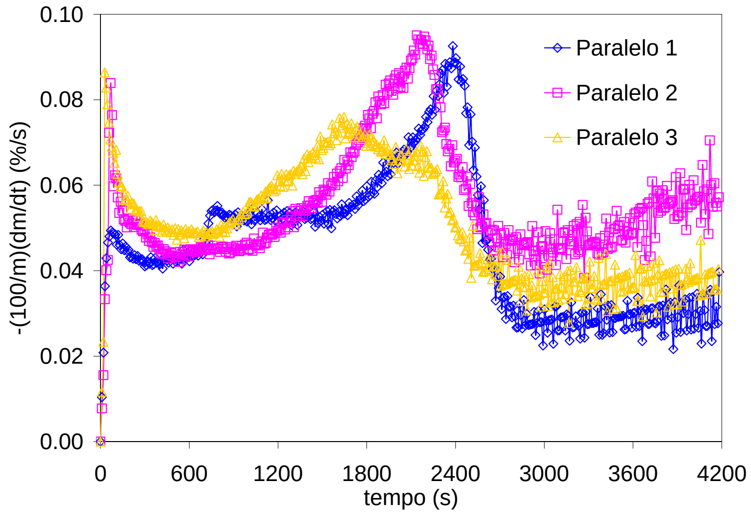

Figure 10 – Percent mass consumption rates of pinus wood slabs with the heated surface parallel to the wood fibers.

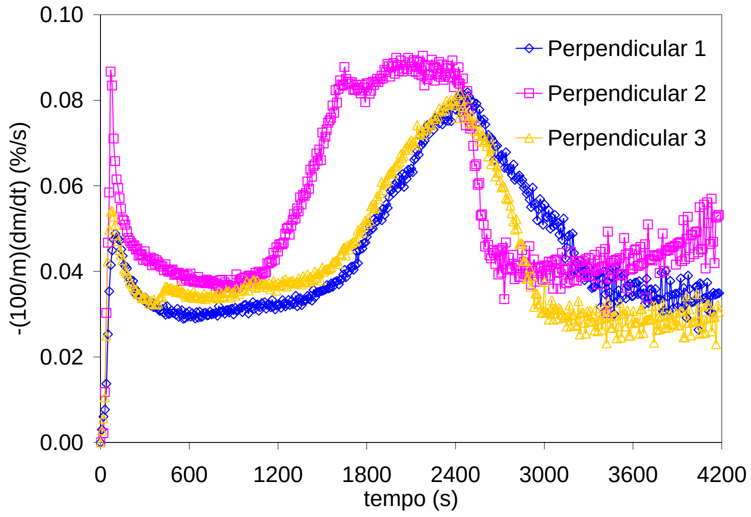

Figure 11 – Percent mass consumption rates of pinus wood slabs with heated surface perpendicular to the wood fibers.

7. Conclusions

Combustion characteristics of pinus wood (*Pinus elliot*) slabs (10x10x5 cm^3) were studied in a conical calorimeter with a heater output of 2000 W. The effects of fiber orientation on drying, self-ignition, pyrolysis, flaming and smoldering were analysed. All samples presented self-ignition and significant flaming. Slabs with fibers perpendicular to the heated surface showed two well-defined pyrolysis regions and presented larger self-ignition times, larger end of pyrolysis times, lower pyrolysis rates (about 10 %) than slabs with fibers parallel to the heated surface. Smoldering rates and char fractions at the end of pyrolysis (flame extinction) were not significantly affected by fiber orientation.

8. Acknowledgement

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9. References

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