EFFECTS OF MOISTURE CONTENT ON BURN RATES AND CHARACTERISTIC TIMES OF BRAZILIAN WOODS

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Abstract. *This work presents experimental data concerning the effects of moisture content on burn rates and combustion characteristic times of four Brazilian woods: pinus (Pinus elliot), eucalyptus (Eucaliptus citriodora), ipê branco (Tabebuia roseo-alba) and embaúba (Cecropia pachystachya). The mass loss rates, percent consumption rates, mass consumption fractions, and times of self-ignition, pyrolysis and flaming were measured by heating cylindrical samples (10 cm length, 3 cm diameter) in a cylindrical calorimeter. The burning behaviours of the four species during pre-heating, drying, self-ignition, pyrolysis, flaming and smoldering are compared and analysed.*

Keywords. Combustion, Brazilian woods, pyrolysis, emissions, cylindrical calorimeter

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 e 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.

Drying is an important step in biomass thermochemical conversion technologies, either as fuel pretreatment carried out through specific units or as a stage of the conversion process, which precedes or takes place simultaneously with chemical reactions. Moisture in wood can exist as free water in the cell cavities, bound water which is hygroscopically held by the cell walls, water vapors in the void space and, finally, constitutive water in the chemical composition within the cell walls. In the drying processes, only free, bound and vapor phase water are removed. Evaporation occurs through effective liquid/vapor sorption isotherms and complex transport phenomena, such as free water capillarity, surface diffusion of bound water and diffusion and convection of water vapors. The role played by moisture transport phenomena is dependent on the heating conditions. Extensive literature on slow drying (temperatures below the normal boiling point of water), carried out for applications in the timber industry and aimed at the achievement of structural wood stability from the green condition, indicate that 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. Some attention has also been given to the high-temperature behavior (generally with degradation/combustion) of moist 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 diameter and heat input on burning characteristics of *Pinus elliot* wood cylinders have been studied experimentally by Castro (2005) and Castro and Costa (2005). 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 tropical biomass and woods under controlled conditions. Therefore, the objective of this work is to determine and compare combustion characteristics of four wood species existent in Brazil: pinus (*Pinus elliot*), eucalyptus (*Eucaliptus citriodora*), ipê branco (*Tabebuia roseo-alba*) and embaúba (*Cecropia pachystachya*). Wood cylinders with different moisture contents were tested inside a specially designed cylindrical calorimeter (Castro, 2005).

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

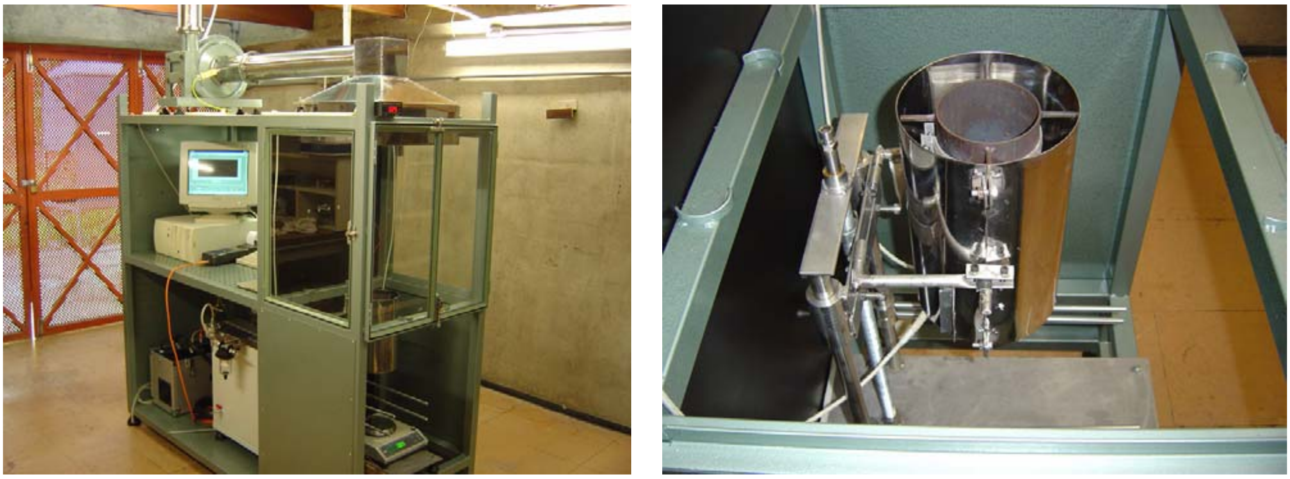
It was built a cylindrical heater apparatus, 10 cm diameter, with two electrical resistances, 1 kW each, as shown in Fig. (1). The system was surrounded by a steel tube, 20 cm diameter, to reduce radiation losses.

A support was positioned inside the heater system and placed on a digital scale, which had a 0.005 g precision and stabilization time less than 2 s. The sample support had a aluminum disc to control the air flux entering the heater system. A steel cylinder was placed on this disk and the wood sample cylinder was placed on it. The steel cylinder eliminated gas recirculation around the wood sample. The scale serial output was linked to a computer. The heater was turned on by a temperature PID controller connected to a thermocouple positioned inside 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 burning cylinders. 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 cylindrical calorimeter and gas sampling system is presented by Castro (2005).



a) b)

Figure 1 – a) Experimental workbench; b) cylindrical calorimeter.

3. Sample Preparation

Wood samples were obtained from pinus (*Pinus elliot*), embaúba (*Cecropia pachystachya*), eucalyptus (*Eucaliptus citriodora*) and ipê branco (*Tabebuia roseo-alba*) 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 3 cm diameter cylinders with 10 cm length, in the direction of the wood fibers. Just after machining the cylinders were packed and frozen again.

Before sample preparation with prescribed moisture levels, the samples were left 24 hr at ambient conditions to attain thermal equilibrium with air (25 ^oC). After that, the samples were oven dried. The oven temperature was set at 103 ^oC, since tests were made at a 600 m altitude. At the sea level the standard temperature is usually 105 ^oC. It is assumed that only moisture is released from wood at this temperature.

The average mass of a set of at least 50 samples was calculated for each species. Due to density variations in the samples, 24 dried samples were selected with standard deviation less than 5 %. Six groups of 4 samples with total dry mass approximately equal were selected. The masses of each group were approximately equal.

After dried, the samples were placed in a pressurized water chamber (1.5 atm) until reach the required moisture content. Dry samples were used in order to reduce the dispersion of samples masses and to assure more similar physical properties among the samples. Table 1 shows the dry masses of wood cylinders of the four species.

Table 1. Dry masses of all selected samples (g).

Moisture content	***Embaúba***	***Pinus***	***Ipê branco***	***Eucalyptus***
0 %	15.65	26.09	33.67	36.83
	16.09	26.12	35.20	37.28
	16.28	26.18	35.60	39.94
	17.12	26.56	35.73	40.87
0 % average	**16.28**	**26.24**	**35.05**	**38.73**
20 %	15.64	26.11	33.88	36.64
	15.87	26.24	35.30	37.26
	16.41	26.33	36.10	39.82
	17.10	26.62	36.70	40.82
20 % *average*	**16.26**	**26.33**	**35.40**	**38.64**
40 %	15.54	25.31	33.89	36.52
	16.08	26.74	35.29	37.09
	16.52	27.33	36.09	38.82
	16.78	26.54	36.39	40.79
40 % *average*	**16.23**	**26.48**	**35.41**	**38.31**
60 %	15.63	25.48	34.03	36.45
	15.70	26.63	35.11	37.05
	16.57	26.79	35.91	38.54
	16.92	27.80	36.38	40.19
60 % *average*	**16.21**	**26.68**	**35.35**	**38.06**
80 %	15.50	25.48	34.81	36.44
	16.14	26.67	35.04	37.04
	16.64	26.81	35.91	37.48
	16.77	27.97	36.20	40.06
80 % *average*	**16.26**	**26.73**	**35.49**	**37.76**
100 %	15.26	25.77	35.00	36.27
	16.18	26.68	35.06	37.03
	16.66	26.90	35.62	37.48
	16.70	28.03	36.18	40.05
100 % *average*	**16.20**	**26.85**	**35.47**	**37.71**
Total Average	**16.23**	**26.55**	**35.38**	**38.20**
Std. Deviation	**0.55**	**0.72**	**0.86**	**1.65**
% Std. Dev.	**3.38**	**2.72**	**2.42**	**4.32**

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 of 470 ^oC, measured by a thermocouple inside the heater. This temperature remained approximately constant up to 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. A sample with known moisture content was unpacked, its mass was verified, and it was rapidly positioned on the sample support inside the 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 and a continuous gas analyzer were started just after the sample was placed on the sample support. Emissions of CO, CO_2, UHC and NO, O_2 concentrations and exhaustion temperatures were measured.

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

5. Results

Several curves of mass evolution for samples with M = 0, 20, 40, 60, 80 and 100 %, on dry basis, for the four species were obtained, as showed in Fig. (2). Data were selected at 10 s intervals, reducing scale stabilization effects.

Figure (3) shows the normalized mass curves, m/m_o, versus time, where m_o is the initial mass.

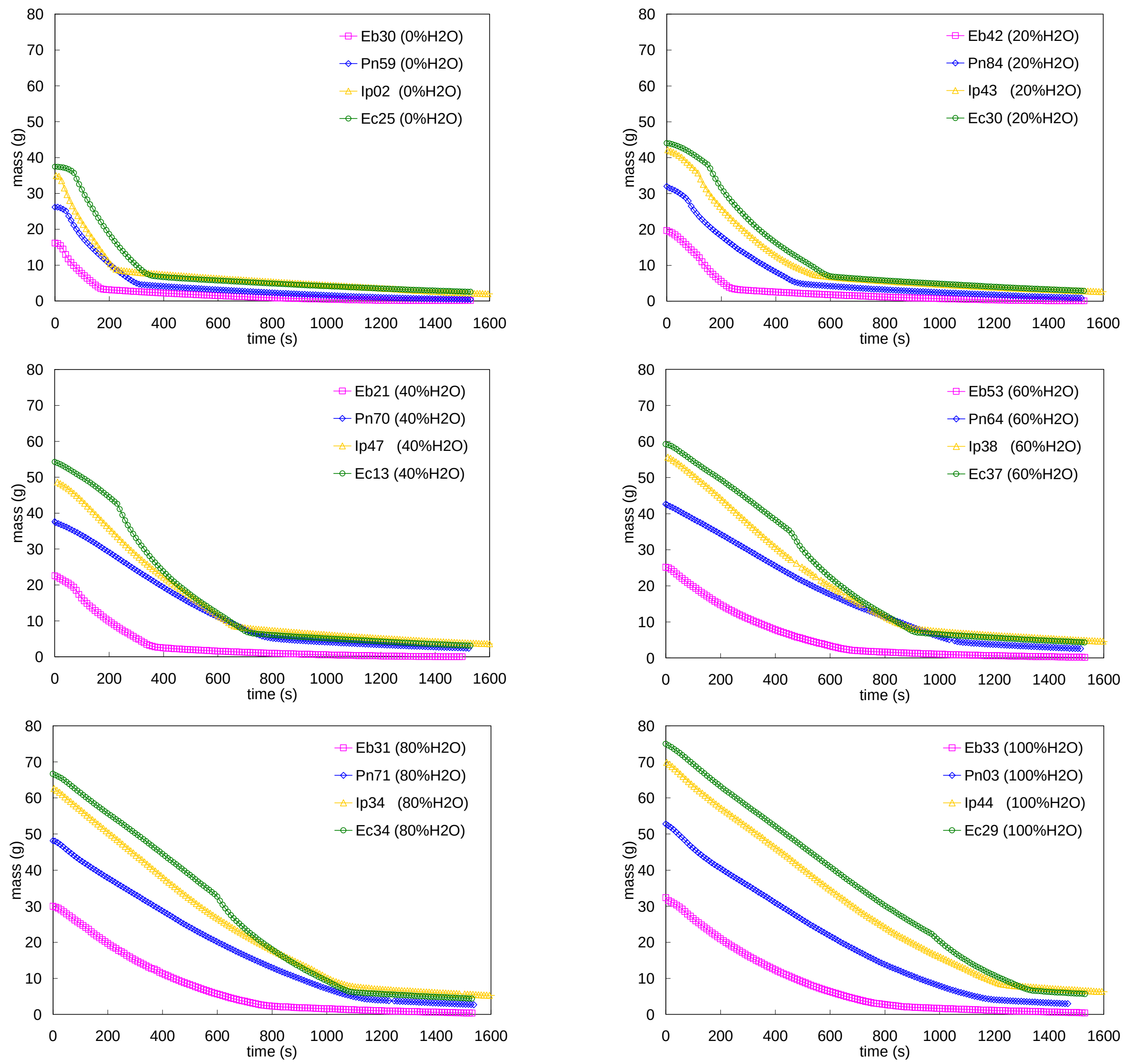


Figure 2 – Mass evolution of embaúba (Eb), pine (Pn), ipê branco (Ip) and eucalyptus (Ec) dowells.

The curves in Figs. (2) and (3) show points of curvature changes. These points indicate the times of self-ignition and times of end of flaming or, if ignition does not occur, the times of end of pyrolysis. After the end of pyrolysis, with or without flaming, the smoldering combustion process begins.

It can be verified in the figures that the moisture levels and initial densities influence the mass evolution of the samples and the times of change of curvature in the plots. In general, samples with larger masses or larger densities require more time for drying and pyrolysis.

The regions of self-ignition and flame extinction are better identified observing the peaks existent on the consumption rates curves ($-dm/dt$) and percent consumption rates curves ($-100dm/dt/m$), as depicted in Figures (4) and (5). The variable m is the instantaneous mass and t is time. If there is no self-ignition these curves do not show peaks, nevertheless the beginning of the pyrolysis phase can be identified by the end of the initial raise in the consumption rates. The end of pyrolysis coincides with the beginning of the smoldering process, when the consumption rates are relatively small. The burning rates during the smoldering process are approximately constant, while the normalized burn rates during smoldering increase slightly with time in most cases. The normalized consumption rates showed strong oscillations in some samples due to the small masses in the smoldering phase, causing fluctuations in the scale weighing. In these cases moving averages were taken to smooth the curves. Embaúba samples had the lowest mass consumption rates, comparing each phase of burning, however presented the largest normalized consumption rates, probably because of the low density. Interestingly, not all embaúba samples presented ignition, despite embaúba having the lowest density among the four species.

It was observed that the moisture content increases the mass data dispersion. Moisture content influences, decreasing, volatile release rates, although it doesn't affect significantly the masses and consumption rates during the smoldering phase. In general, the samples kept an approximate cylindrical shape during most of the burning process, despite the formation of cracks on the surface.

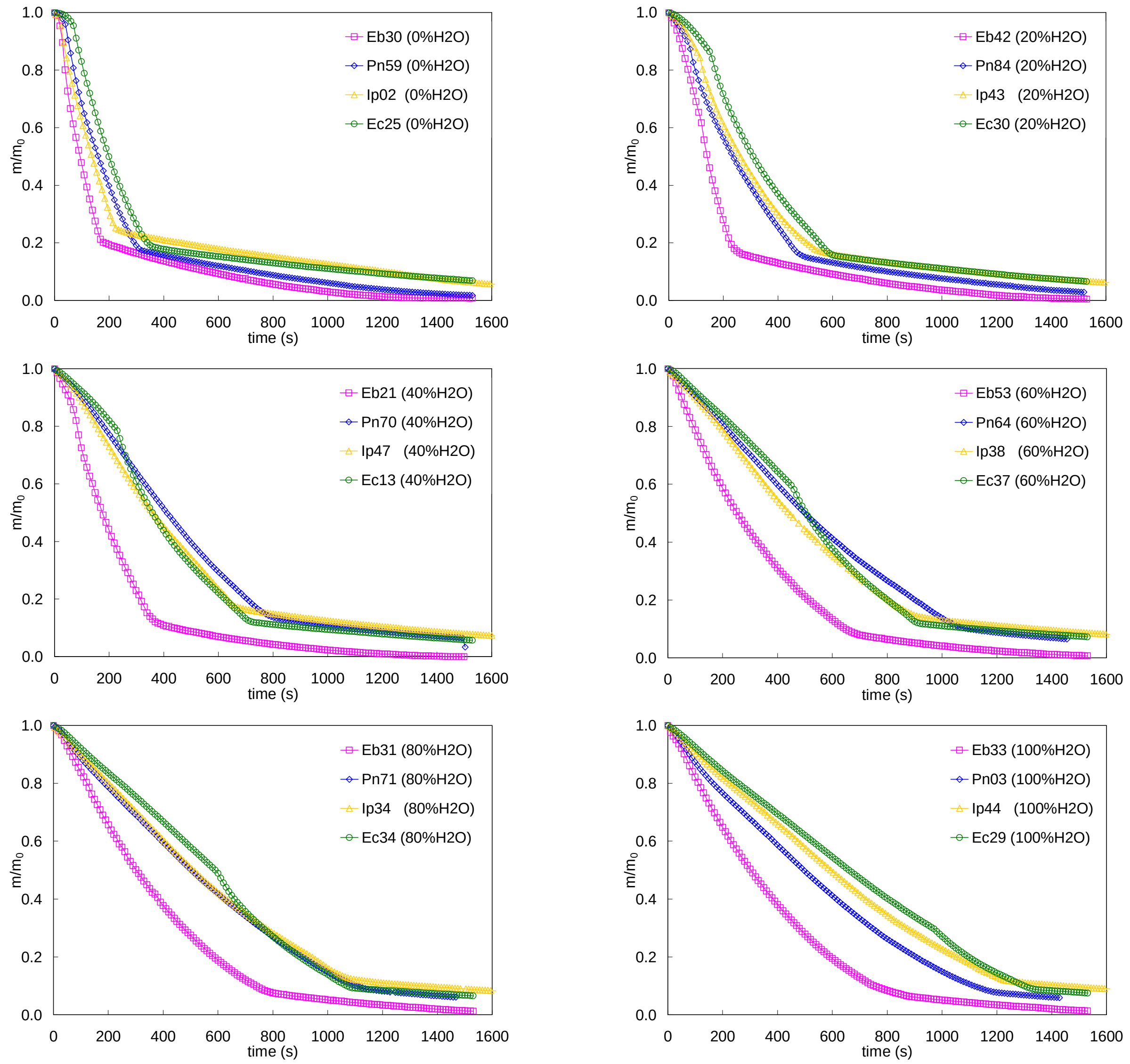


Figure 3 – Normalized mass evolution during burning of embaúba (Eb), pine (Pn), ipê branco (Ip) and eucalyptus (Ec) dowels.

All dry samples and samples with 20 % moisture content, depicted in the figures 2 to 5, presented ignition, while only the embaúba and eucalyptus samples with 40 % moisture content presented ignition. All eucalyptus samples presented ignition, independently of the moisture content. This can be possibly explained by the volatiles composition and larger volatiles release rate, creating a mixture above the lean flammability limit in the boundary layer around the cylinder.

During flaming the mass derivatives and normalized consumption rates keep an approximately parabolic shape. The consumption rates are larger for flaming than for pyrolysis without flaming, as a consequence of the additional heating by the flame.

Table 2 shows a summary of characteristic data for the different species. Initial sample masses, end of pyrolysis masses and the initial percentage of char in the smoldering phase, wet basis, of all samples are showed. The consumption rates at start of pyrolysis, end of pyrolysis and at start of smoldering are also showed.

It can be seen in Table 2 that moisture content affects the sample mass at the end of pyrolysis. Char fractions on wet basis decrease with moisture content, as expected. However, the char fractions on dry basis of ipê branco and eucalyptus samples increase with increasing moisture content.

It is verified in Table 2 that consumption rates during flaming can be three times higher than consumption rates without flaming.

All samples with moisture contents of 0 and 20% started pyrolysis near the self-ignition point. For the moisture content of 40%, only embaúba and eucalyptus samples presented pyrolysis near the self-ignition point, having larger pyrolysis rates in the start of pyrolysis. For eucalyptus samples with moisture contents above 40 % flaming happened later in the pyrolysis phase.

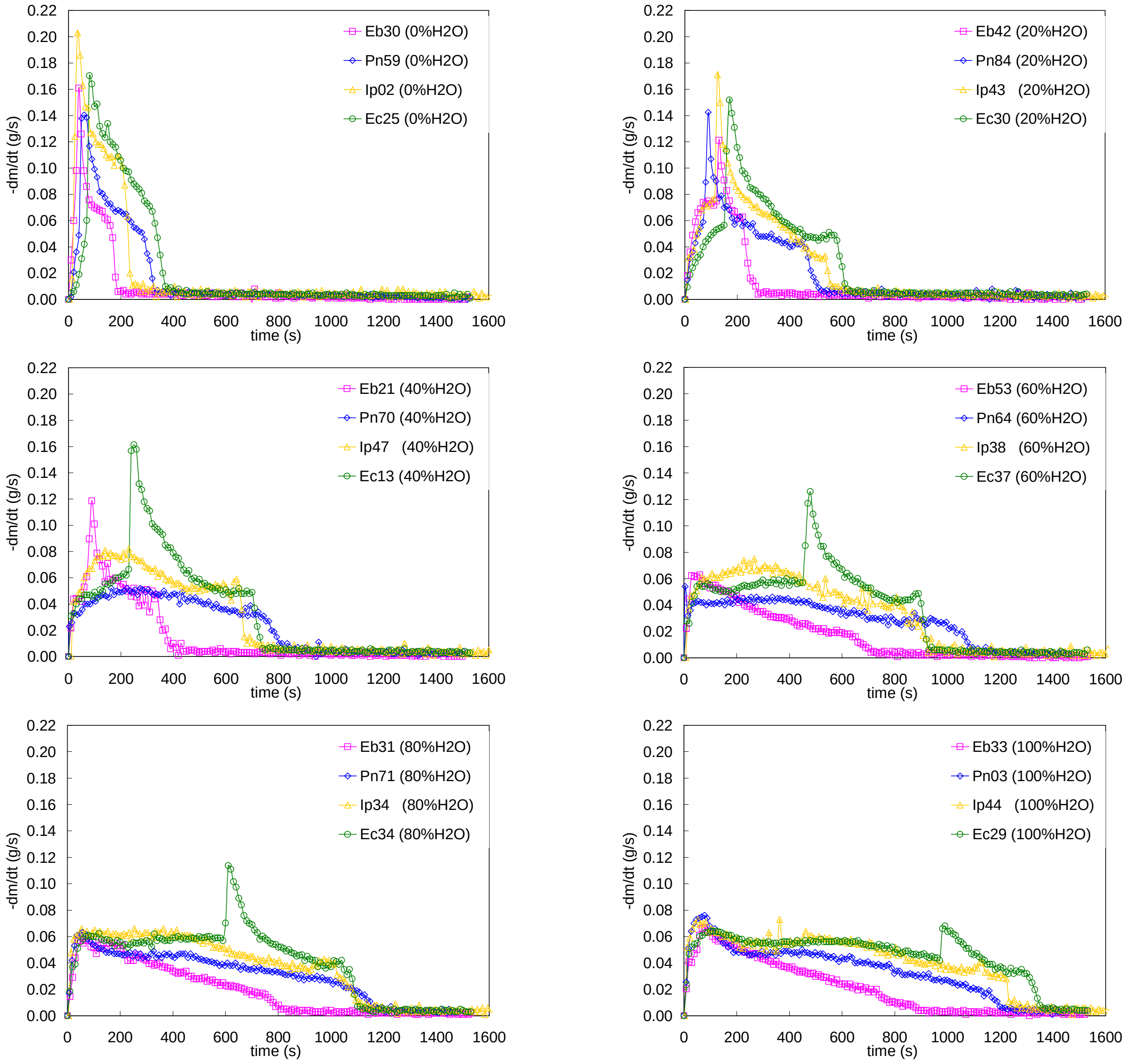


Figure 4 – Mass consumption rates of burning of embaúba (Eb), pine (Pn), ipê branco (Ip) and eucalyptus (Ec) dowels.

Figure (6) shows the times of ignition and times of pyrolysis with or without flaming. Samples with lower levels of moisture presented small self-ignition times. Nevertheless, there was always some residual water inside the cells and cell walls, with consequent water release in all cases.

The times of end of pyrolysis of ipê branco cylinders increased from about 200 s for dry samples to about 1200 s for samples with 100 % moisture content. Dry pinus samples finished pyrolysis in about 400 s while pinus samples with 100 % moisture content finished pyrolysis en 1200 s. Therefore moisture increased 3 to 6 times the end of pyrolysis times, from 0 to 100 % of moisture, dry basis.

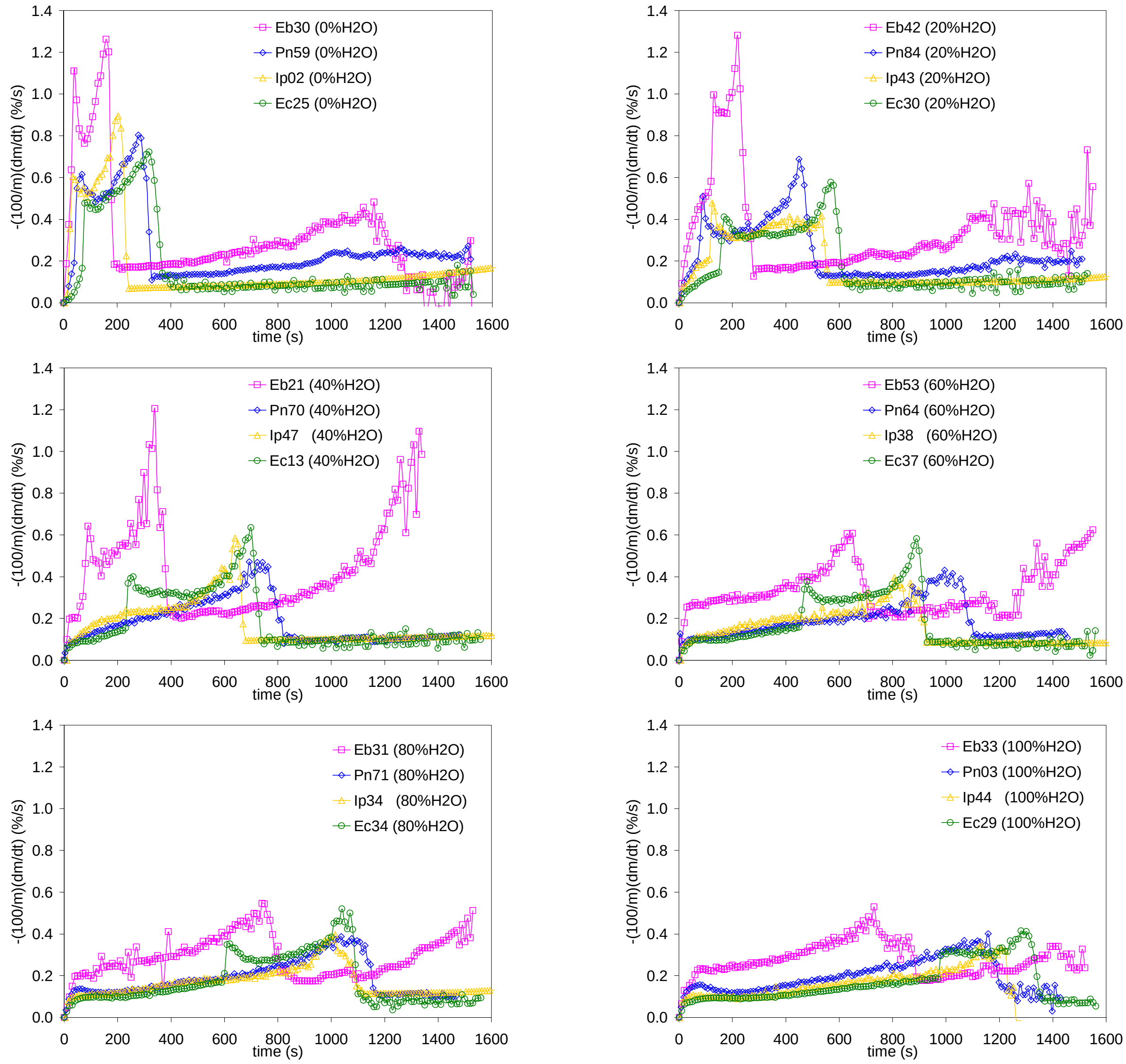


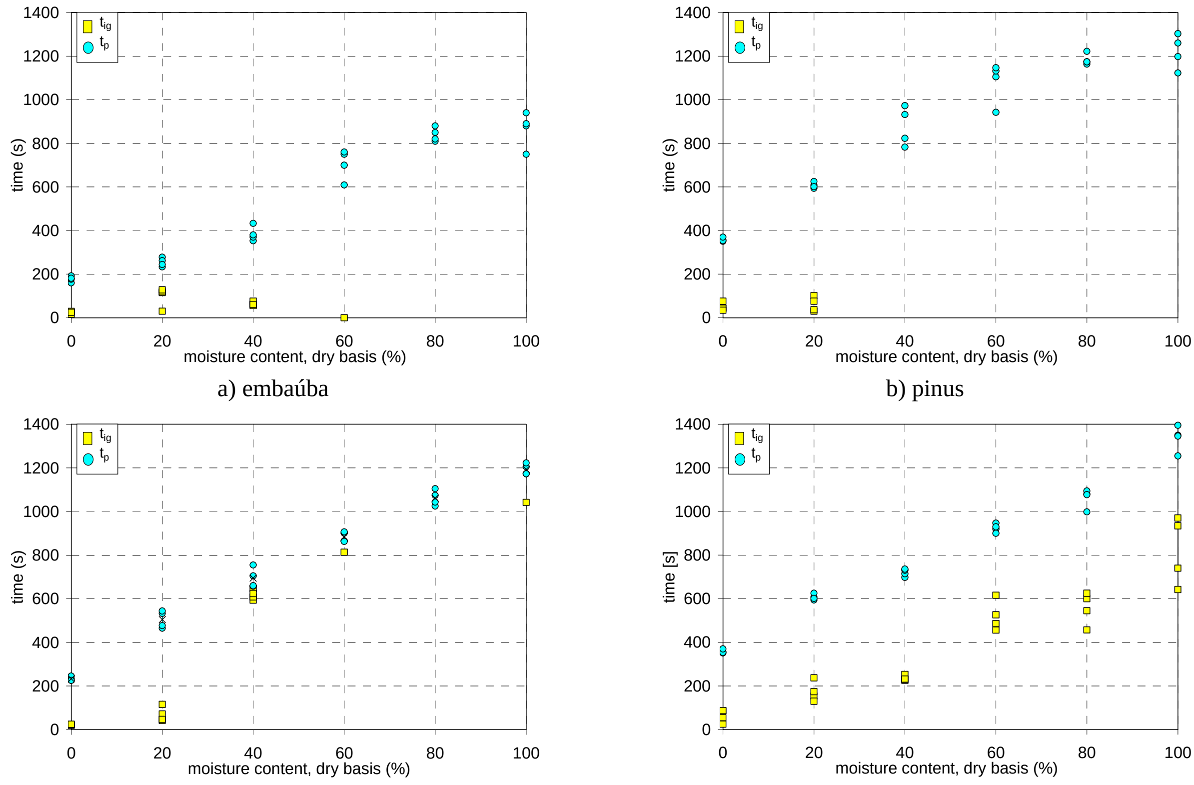
Figure 5 – Normalized consumption rates of burning of embaúba (Eb), pine (Pn), ipê branco (Ip) and eucalyptus (Ec) dowels.

Table 2. Comparative data of all samples.

Samples	**Initial mass (g)**	**End of pyrol. mass (g)**	**Char fraction**	**Consumption rates (g/s)**		
				Pyrol. start	**End of pyrol.**	**Smolder. start**
Eb 0%	16	3	0.19	0.18*	0.06	0.01
Pn 0%	26	5	0.19	0.16*	0.04	0.01
Ip 0%	35	8	0.23	0.21*	0.11	0.01
Ec 0%	38	7	0.18	0.18*	0.09	0.01
Eb 20%	20	3	0.15	0.12*	0.06	0.005
Pn 20%	32	4	0.13	0.14*	0.04	0.005
Ip 20%	42.5	7.5	0.18	0.18*	0.03	0.01
Ec 20%	47.5	7.5	0.16	0.16*	0.04	0.01
Eb 40%	27.5	2.5	0.09	0.12*	0.04	0.005
Pn 40%	37.5	5	0.13	0.05	0.02	0.05
Ip 40%	48	9	0.19	0.08	0.04	0.01
Ec 40%	55	7.5	0.14	0.16*	0.05	0.01
Eb 60%	26	2.5	0.10	0.07	0.02	0.005
Pn 60%	42.5	6	0.14	0.05	0.02	0.005
Ip 60%	55	10	0.18	0.07	0.04	0.01
Ec 60%	60	7.5	0.13	0.06	0.05	0.01
Eb 80%	28	2.5	0.09	0.07	0.01	0.0025

Pn 80%	50	7.5	0.15	0.07	0.02	0.005
Ip 80%	62.5	10	0.16	0.06	0.04	0.01
Ec 80%	68	7.5	0.11	0.065	0.04	0.005
Eb 100%	32	2.5	0.08	0.06	0.01	0.003
Pn 100%	53	5	0.09	0.075	0.025	0.005
Ip 100%	70	10	0.14	0.07	0.04	0.01
Ec 100%	75	10	0.13	0.07	0.045	0.01

* pyrolysis begins point near the self-ignition point.



a) embaúba
b) pinus
c) ipê branco
d) eucalyptus

Figure 6 – Self-ignition, t_{ig}, and pyrolysis times, t_p, with or without flaming.

Additional data concerning CO, CO_2 and NO emissions, oxygen consumption and exhaustion temperatures for the samples presented in this paper are given by Castro (2005).

7. Conclusions

The combustion characteristics of four woods existent in Brazil were analysed. Wood cylinders, 3 cm diameter and 10 cm length, of pinus (*Pinus elliot*), eucalyptus (*Eucaliptus citriodora*), ipê branco (*Tabebuia roseo-alba*) and embaúba (*Cecropia pachystachya*) were burned in a cylindrical calorimeter with a heat output of 2000 W. The effects of moisture content on drying, self-ignition, pyrolysis, flaming and smoldering of the different species were considered. Embaúba samples presented self-ignition and significant flaming for 0, 20 and 40 % moisture content, pinus and ipê branco samples presented significant flaming for 0 and 20 % moisture content, and Eucalyptus samples presented self-ignition for all moisture contents. Embaúba, the wood with lowest density, burned faster than the others species. Pinus and eucalyptus samples presented similar total drying-pyrolysis times for all moisture contents. Increasing the moisture content from 0 to 100 %, dry basis, increased 3 to 6 times the pyrolysis times, with or without flaming, while did not affect significantly the smoldering rates.

8. Acknowledgement

The authors acknowledge FAPESP for supporting this research.

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