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BURNING CHARACTERISTICS OF WOOD CYLINDERS

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Abstract. This work describes an experimental and theoretical investigation of drying, self-ignition, flaming and smoldering of pine and embaúba cylinders, under a constant heat flux. The effects of moisture content on characteristic times, mass evolution and consumption rates are analyzed. Pine cylinders present self-ignition at all moisture levels, while embauba cylinders presented flaming only for moisture content below 30 %. It is verified that the moisture content influences all phases of the process. The char oxidation process was better described by the theoretical solution adopting a surface reaction with the mass transfer coefficient inversely proportional to the cylinder diameter. Other experimental aspects could be reasonably represented by the simplified theoretical model.

Keywords. combustion, wood, flame, smoldering, biomass

1. Introduction

Combustion of biomass in fires releases a large amount of pollutants in the atmosphere, increasing global warming, acid rain formation, smoke production 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).

Intense clearing fires occur annualy in the Brazilian Amazonia deforestation arc, between May and September, aiming the preparation of land for use in agriculture and cattle pasture. The felled vegetation is sun dried maintaining different levels of moisture, thus influencing the burning process and the composition and amount of the gases released, which also depend on physical and chemical characteristics of wood. Long droughts increase the risks of forest fires, like those occurred in the Roraima State in 1996 and 2003, which have devastated large areas.

The research group on forest fires of the Combustion and Propulsion Associated Laboratory from INPE has been investigating in the last years several aspects of fires in the Brazilian Amazonia, by means of prescribed burns (Costa et al., 2000; Carvalho et al., 2000). These studies have not focused yet on the characterization of different species under fire conditions, determining their individual behavior during all phases of burning. Moisture content, porosity and other chemical and physical characteristics can affect the mass loss rate, the release of volatiles and the formation of products during combustion.

In the other hand the utilization of wood in structures, buildings, houses, thermal protection and furnitures increases the risks of fires. Therefore it is of great interest to investigate the burning of wood and cellulosic materials, in general, in order to prevent fires in residences, industries and buildings.

Combustion of biomass presents several phases: pre-heating, drying, ignition, pyrolysis, flaming and smoldering. Flaming occurs after ignition during pyrolysis. Smoldering is a flameless burning process that can last several days after fires, specially in the case of large logs or ground vegetation.

Several theoretical, numerical and experimental works were made about the phases of burning of wood. Among others, Tinney (1965), Trabaud (1976), Kanury (1994), Yokelson et al. (1996), Sastamonien and Richard (1996), and Spearpoint (1999) have made contributions concerning the pyrolysis and burning of woods from cold and temperate weather regions. Tinney (1965) compared simplified numerical results, using a thermic model, with experimental results obtained from burning cylindric wood samples under heated air. Trabaud (1976) determined times of ignition and burning of bush samples from the Mediterranean region of France. Kanury (1994) developed a simplified theoretical model concerning the several phases of biomass burning. Yokelson et al. (1996) measured the emissions during flaming and smoldering of various kinds of biomass. Saastamonien and Richard (1996) presented detailed numerical simulations of simultaneous drying and pyrolysis of biomass. Spearpoint (1999) determined combustion characteristics of cellulosic materials using a conic calorimeter and validated an integral model of ignition and pyrolysis.

The objective of this work is to compare all phases of the burning process of pine and embauba cylinders, and to perform a theoretical analysis of the process under a constant heat flux and self-ignition. The embaúba is a common Brazilian softwood, with several sub-species, occurring in most regions of Brazil.

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

2. Experimental Setup

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

A support was positioned inside the heater system and placed on a digital scale, with a 0.005 g precision and stabilization time less than 2 s. The support had on its top a aluminum disc to control the air flux entering the heater system, and also a steel cylinder where the wood cylinder was placed, to avoid gas recirculation on the wood sample, as shown in Fig. 1. The scale serial output was linked to a notebook computer which registered the weighing data.

The heater was turned on by a temperature controller connected to a thermocouple positioned inside the heater, outside the flame zone.

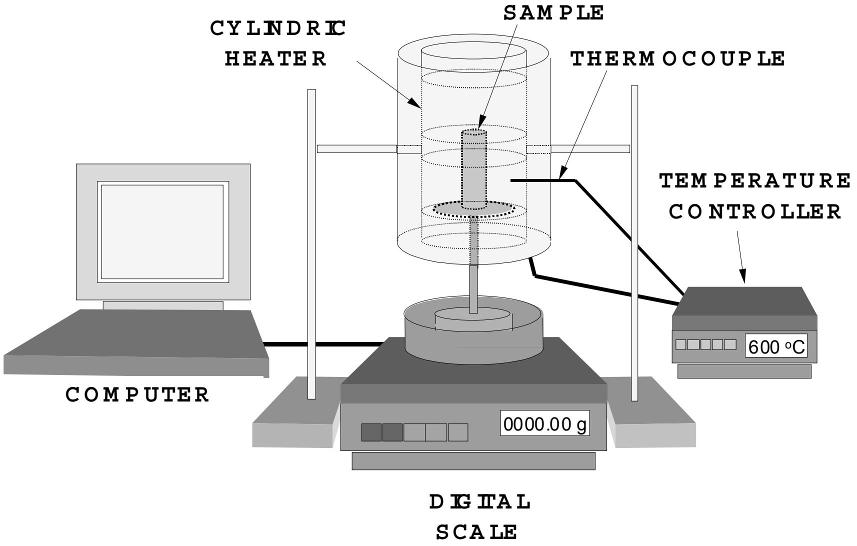


Figure 1 – Experimental setup.

3. Sample Preparation

Wood samples were obtained from pine (*Pinus elliot*) and embaúba (*Cecropia pachystachya*) trees, recently cut. The logs were cut in 60 cm dowells, which were packed and frozen until machining. Freezing reduced moisture losses and wood deterioration, and yielded better 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.

Due to any inclusions and density variations in the samples, only samples with mass within ± 3 % of the average mass of a set of 40 samples were selected. Before ovendrying the samples were left 24 hr at ambient conditions to attain thermal equilibrium with air (25 ^{o}C). The oven temperature was set at 103 ^{o}C, since tests were made at 600 m altitude. At the sea level the standard temperature is usually 105 ^{o}C. It is believed that only moisture is released from wood at this temperature. After obtaining drying curves for each wood species, the test samples were prepared by ovendrying them until the required moisture contents, M = 0 to 50 %, on wet basis:

$$M = \frac{m_{H2O,0}}{m_{H2O,0} + m_d} \tag{1}$$

where m_d is the dry mass and $m_{H2O,0}$ is the initial mass of water inside the wood cylinder. The wood samples with known moisture contents were packed and frozen. The measured ovendry density of the pine cylinders was 324 kg/m^3 and the measured ovendry density of the embaúba cylinders was 424 kg/m^3.

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 heater system was closed at its top by a metal disk to allow a faster heating. The heater was turned on until reaching a temperature of 500 ^oC, measured by the thermocouple inside the heater, as showed in Fig. (1). The heater was left at 500 ^oC for 5 minutes and then the metal cover was removed. The heater system reduced its temperature to 430 ^oC, by natural convection, and then remained at this temperature up to flaming.

The samples were unfrozen 24 hr before the test. A sample with a known moisture content was unpacked, verified its mass and 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, under a constant heat flux, simulating fire conditions.

Natural convection caused by electrical heating, flaming or smoldering brought cold air from the ambient into the heater thus keeping the burning process.

5. Results

Several curves of mass evolution for pine and embauba samples with M = 0, 10, 20, 30, 40 and 50 % were obtained, as showed in Fig. (2). The 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.

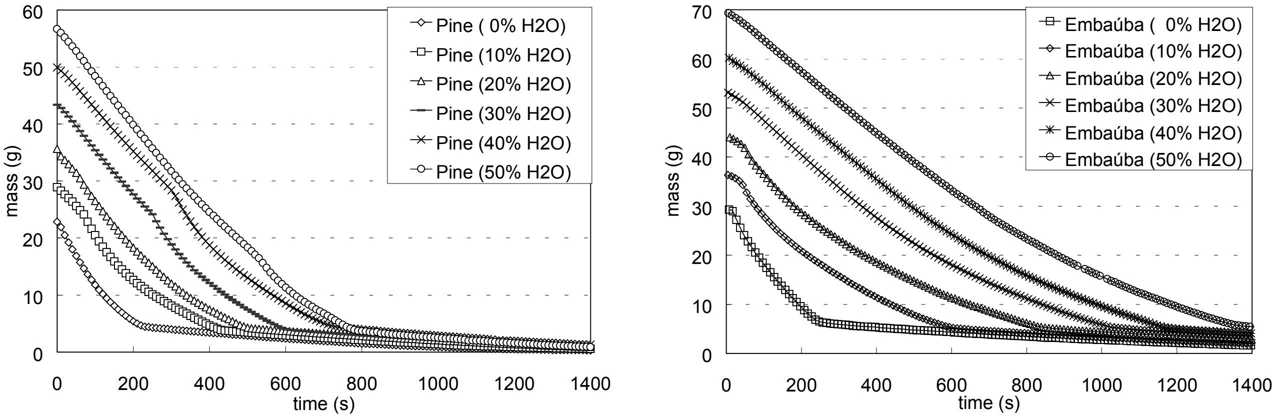


Figure 2 – Mass evolution during burning of pine and embaúba dowells.

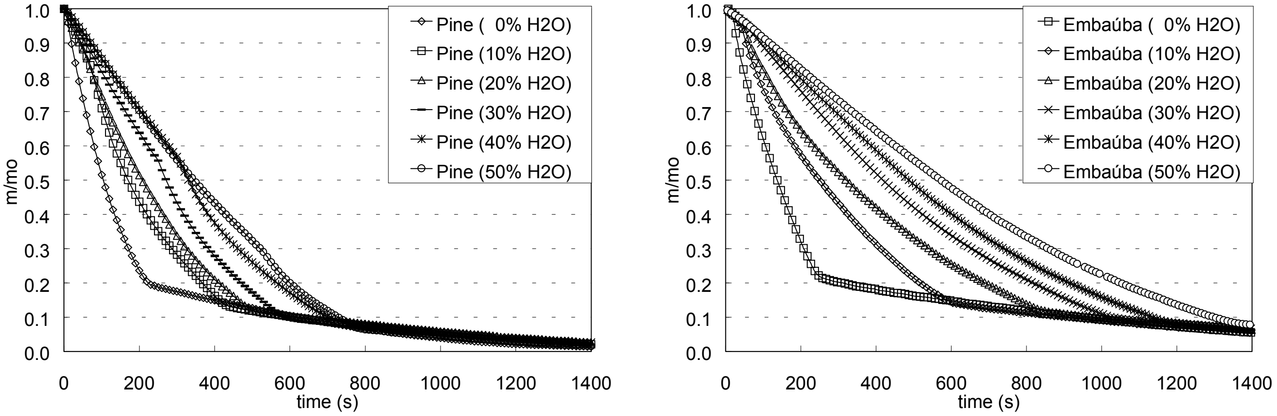


Figure 3 – Normalized mass evolution during burning of pine and embaúba dowells.

It is seen in Figs. (2) and (3) that moisture levels influence the mass evolution of the samples and the times where can occur a change of curvature in the plots. These times indicate the self-ignition and the end of flaming. In the case of embauba samples with moisture contents above 30 % there is no clear self-ignition, probably due to a small mass flux of volatiles or the simultaneous release of water and volatiles at significant levels. It should be noted that it is required a minimum flux of volatiles to attain the lower limit of flamability of the gaseous mixture and to cause self-ignition in the boundary layer adjacent to the wood cylinder (Kanury, 1977).

The normalized mass is about 8 % at 800 s, for all pine samples, and 8% at 1400 s, for all embauba samples. All curves superpose thereafter in both cases. This could indicate that both wood species contain the same amount of ash.

Figure (4) shows the mass consumption rates of the samples, $CR = -dm/dt$, versus time. During flaming the mass derivatives have a parabolic shape and after its end, during smoldering, the mass consumption rate is approximately constant or decreases sligthly.

Since the mass of the samples change with time it was also defined a normalized consumption rate:

$$NCR = -\frac{100}{m}\frac{dm}{dt} \qquad (2)$$

Figure (5) shows the normalized consumption rates versus time for pine and embauba samples. It is seen that the pyrolysis region where flaming occurs keeps a parabolic shape, as in the mass derivative plots. In the case of the pine sample with 0 % moisture and for the embaúba samples with moisture content above 30 % a linear fit can be obtained for the pyrolysis phase. Alternatively, the parabolic shape could be replaced by two linear fits in the other cases. The self-ignition and end of flaming points can be easily identified. Normalized smoldering rates attain a maximum between 1200 and 1400 s for pine samples, while embauba samples present decreasing normalized smoldering rates for wood cylinders with moisture content above 30 % and increasing smoldering rates for moisture contents below 30 %.

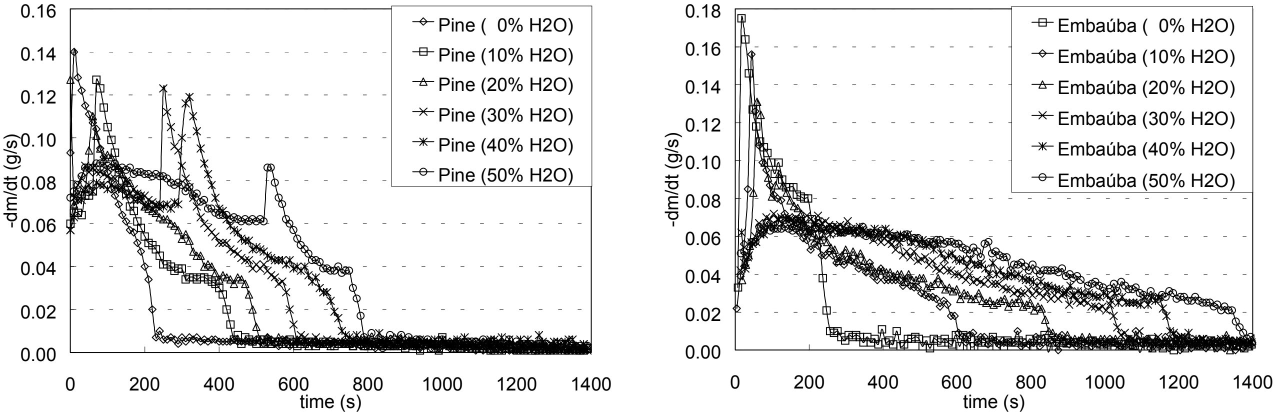


Figure 4 – Mass consumption rates of burning dowells of pine and embaúba.

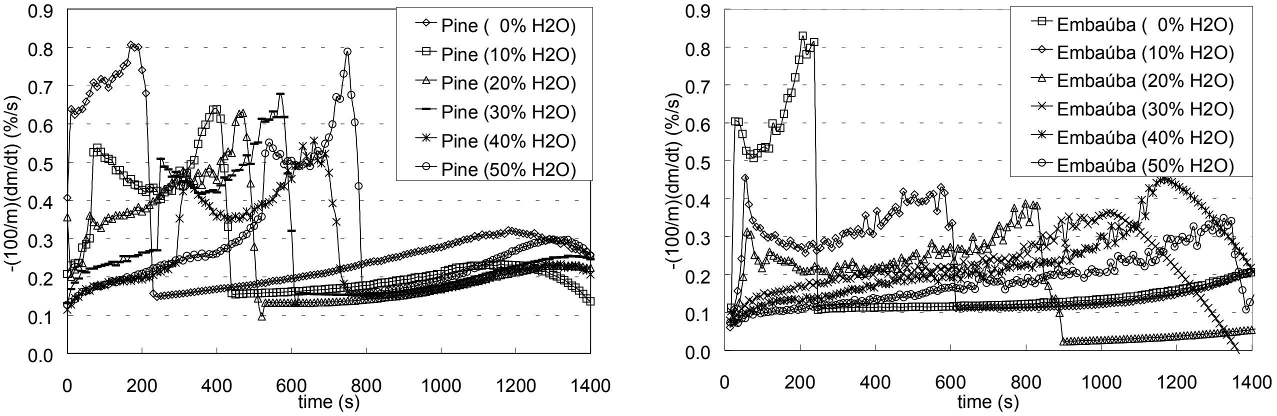
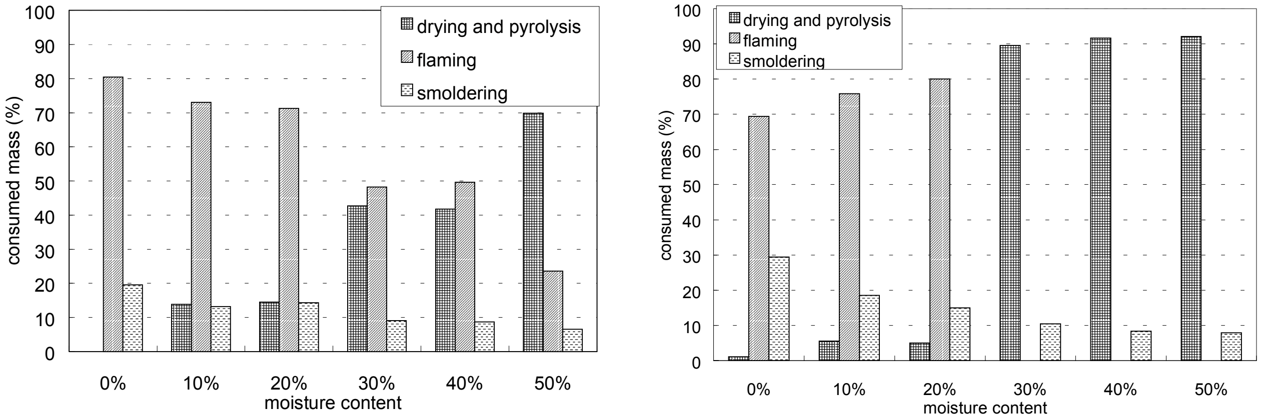


Figure 5 – Normalized consumption rates.

It was observed that samples kept an approximate cylindrical shape during the entire burning process, despite formation of cracks on their surfaces.

Samples with lower levels of moisture have very small self-ignition times. Nevertheless, there is always some water inside the cells and cellwalls, with release of water in all cases.

Figure (6) shows the fraction of mass consumed at each phase for all samples and Fig. (7) shows the ignition and pyrolysis times with or without flaming. In Fig. (6) the mass consumed by smoldering is assumed as the difference between the initial mass and the mass loss after drying and pyrolysis. Thus, the ash mass was neglected.



a) pine dowells

b) embaúba dowells

Figure 6 – Consumed mass in the different phases of burning of pine and embaúba dowells.

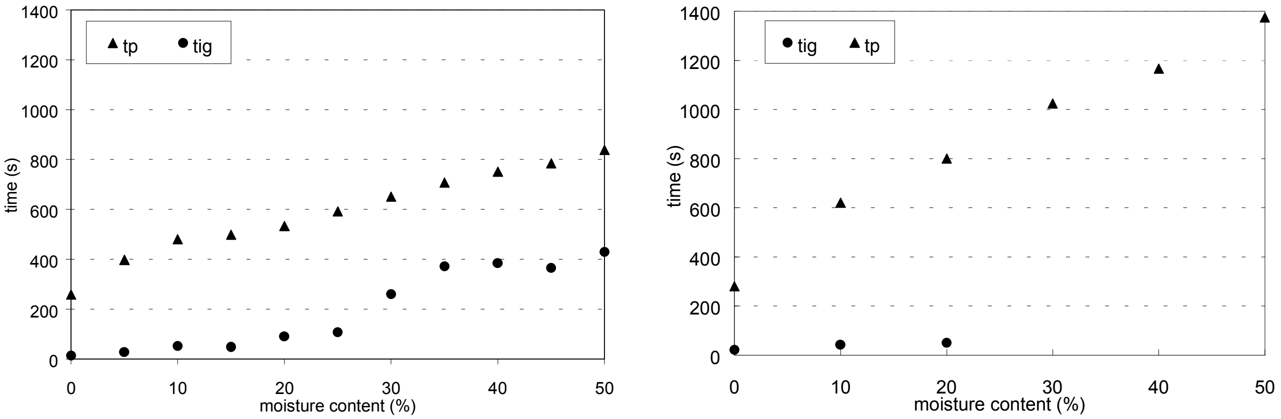


Figure 7 – Self-ignition, t_{ig}, and pyrolysis times, t_p, with or without flaming.

For the pine samples the maximum fraction of consumed mass is about 80 %, occurring during the flaming period in the sample with 0 % moisture. In the case of embauba cylinders the maximum fraction of consumed mass is about 90 %, occurring during pyrolysis for all moisture contents above 30 %.

The flaming time is approximately constant for moisture contents between 10 and 25 % for the pine samples, with a minimum at 35 %. End of pyrolysis times increase linearly with time for embaúba samples above 10 % moisture. It can be observed that close to the fiber saturation point (FSP), M ≈ 30 %, the ignition times of the pine samples appear to have a local maximum. It was verified that the dispersion of data above the FSP of pine is much larger than below the FSP.

Ignition times of pine cylinders appear to grow approximately linearly with moisture content up to the FSP. However the ignition times of embauba cylinders grow linearly up to 20 % moisture and afterwards there is no ignition.

6. Theoretical Model

A simplified theoretical model for heating, drying, pyrolysis, flaming and smoldering of wood cylinders under a constant heat flux F_o (W/m^2) was developed based on a previous model for wood spheres presented by Kanury (1994), using balance equations for energy and mass.

Assuming a constant property infinite cylinder with initial radius a, no contraction and no cracks formed on its surface, the following expressions for the characteristic times and consumption rates are obtained:

Pre-heating:

$$t_{iv} \cong \frac{\rho_f c_{p,f} a (T_v - T_o)}{2F_o} + \frac{a^2}{\alpha_f}\left(\frac{1}{8} + \sum_{i=1}^{\infty} \frac{1}{z_i^2 J_0(z_i)} e^{-\frac{z_i^2 \alpha_f t_{iv}}{a^2}}\right) \tag{3}$$

where t_{iv} is the pre-heating time, T_v is the vaporization temperature (~373 K), T_o is the initial temperature of the wood cylinder, J_0 is the Bessel function of order zero, z_i are the zeroes of the Bessel function J_1, α_f is the green wood diffusivity, $c_{p,f}$ is the specific heat of the green wood and ρ_f is the green wood density.

Equation (3) shows that the pre-heating time is proportional to wood specific heat, wood density, vaporization temperature and to cylinder radius. On the other hand the pre-heating time varies inversely to the thermal diffusivity and to incident heat flux. The green wood density and the wood specific heat increase with moisture content.

Drying:

$$t_d \cong \frac{L_v a \rho_d (1+M)}{2\alpha_f F_o} \tag{4}$$

$$\dot{m}_d = -\frac{2\pi a l_c F_o}{L_v} \tag{5}$$

where t_d is the drying time, L_v is the heat of vaporization, ρ_d is the dry wood density, $\dot{m}_d$ is the mass consumption rate of the dry wood, and l_c is the length of the cylinder.

Equation (5) shows that the drying time is proportional to the cylinder radius, moisture content and inversely proportional to the heat flux, similar to pre-heating time. The theoretical mass consumption rate is constant which is not exactly the same found in the experiments.

Pyrolysis with flame:

$$t_{p,fl} = \frac{\rho_d c_{p,d} a (T_p - T_v)}{2(F_o + F_{fl})} + \frac{a^2}{\alpha_d}\left(\frac{1}{8} + \sum_{i=1}^{\infty} \frac{1}{z_i^2 J_0(z_i)} e^{-\frac{z_i^2 \alpha t_{p,fl}}{a^2}}\right) \tag{6}$$

$$\dot{m}_p = -2\pi r_p l_c (\rho_d - \rho_c) \frac{dr_p}{dt} \tag{7}$$

with

$$\frac{a}{\alpha_d}\frac{dr_p}{dt} = \frac{1 + \sum_{i=1}^{\infty} \frac{J_0(z_i r_p / a)}{J_0(z_i)} e^{-\frac{z_i^2 \alpha_d t}{a^2}}}{\frac{r_p}{2a} + \sum_{i=1}^{\infty} \frac{J_1(z_i r_p / a)}{z_i^2 J_0(z_i)} e^{-\frac{z_i^2 \alpha_d t}{a^2}}} \tag{8}$$

where t is time, $t_{p,fl}$ is the pyrolysis time with flaming, $c_{p,d}$ is the specific heat of the dry wood, α_d is the thermal diffusivity of the dry wood, r_p is the radius of the pyrolysis front, F_{fl} is the heat flux from the flame zone, ρ_d is the dry wood density and ρ_c is the char density.

Equation (6) shows that the flaming time is inversely proportional to the flame temperatures, wood diffusivity and to the incident heat fluxes, and that it is directly proportional to dry wood density, dry wood specific heat and diameter and pyrolysis temperature. It can be verified that mass consumption rates are approximately constant with time.

Smoldering:

After pyrolysis the wood cylinder is supposed to be completely converted into char. Following the pyrolysis the smoldering process begins with the char reacting with oxygen diffusing across the adjacent boundary layer.

If the char oxidation occurs only at the char surface, it is convenient to define a mass transfer coefficient, h_d:

$$\dot{m}''_{ox} = h_d (Y_{ox,a} - Y_{ox,s}) \tag{9}$$

where $\dot{m}''_{ox}$ is the mass flux of oxygen per unit area, $Y_{ox,a}$ is the mass fraction of oxygen at the free stream and $Y_{ox,s}$ is the mass fraction of oxygen at the char surface.

i) For constant h_d, it follows that

$$t_{s,1} \cong \frac{\rho_c a}{f h_d Y_{ox,a}} (1 - (m_a / m_c)^{1/3}) \tag{10}$$

$$\dot{m}_{s,1} = -2\pi a l_c f h_d Y_{ox,a} \left(1 - \left(f h_d Y_{ox,a} / \rho_c a\right)(t - t_c)\right) \tag{11}$$

$$m_{s,1} = m_c \left[1 - \left(f h_d Y_{oxa} / \rho_c a\right)(t - t_c)\right]^3 \tag{12}$$

where f is the stoichiometric mass ratio between carbon and oxygen, t_c is the time where smoldering starts, m_a is the final mass of the char (supposed ash), m_c is the initial mass of char (after flaming or pyrolysis), $t_{s,1}$ is the smoldering time, $m_{s,1}$ is the mass of the cylinder and $\dot{m}_{s,1}$ is the mass consumption rate for case i. In this case the mass consumption rate is linear with time and the sample mass varies with t^3.

ii) For $h_d \approx 1/a$, it yields:

$$t_{s,2} \cong \frac{\rho_c a^2}{2 f \rho_g D_{og} Y_{ox,a}} (1 - (m_a / m_c)^{2/3}) \tag{13}$$

$$\dot{m}_{s,2} = -2\pi a l_c f h_d Y_{ox,a} \left(1 - \left(2 f \rho_g D_{og} Y_{ox,a} / \rho_c a^2\right)(t - t_c)\right)^{1/2} \tag{14}$$

$$m_{s,2} = m_c \left[1 - \left(2 f \rho_g D_{og} Y_{oxa} / \rho_c a^2\right)(t - t_c)\right]^{3/2} \tag{15}$$

where D_{og} is the diffusion coefficient of oxygen in the gas at the boundary layer, ρ_g is the gas density, $t_{s,2}$ is the smoldering time, $m_{s,2}$ is the mass of the cylinder and $\dot{m}_{s,2}$ is the mass consumption rate for case ii. In this case the mass consumption rate varies with $t^{1/2}$ and the sample mass varies with $t^{3/2}$.

We assume now that reaction occurs inside the char pores. To analyze this case it is defined the Biot number:

$$Bi_a = \frac{a h_d \ln(a / r_c)}{\rho_g D_{op}} \tag{16}$$

which represents the ratio between external resistance to oxygen diffusion at the boundary layer and the internal resistance to oxygen diffusion into the pores. D_{op} is the oxygen diffusivity inside the pores and r_c is the radius of the char core. Outside the char core there is only ash.

iii) $Bi_a << 1$

$$t_{s,3} \cong \frac{(\rho_c - \rho_a) a}{2 f h_d Y_{ox,a}} \tag{17}$$

$$\dot{m}_{s,3} = -2\pi a l_c f h_d Y_{ox,a} \tag{18}$$

$$m_{s,3} = m_c - 2\pi a l_c f h_d Y_{oxa} (t - t_c) \tag{19}$$

where $t_{s,3}$ is the smoldering time, $m_{s,3}$ is the mass of the cylinder and $\dot{m}_{s,3}$ is the mass consumption rate for case iii. In this case the mass consumption rate is constant and the sample mass varies linearly with t.

iv) $Bi_a >> 1$

$$t_{s,4} \cong \frac{(\rho_c - \rho_a)(1+0.25a^2)}{f\rho_g D_{op} Y_{ox,a}} \tag{20}$$

$$\dot{m}_{s,4} = -\frac{2\pi l_c f\rho_g D_{op} Y_{ox,a}}{\ln a - \ln r_c} \quad \text{with} \quad r_c \ln(a/r_c)\frac{dr_c}{dt} = -\frac{f D_{op} Y_{ox,a}\rho_g}{\rho_c - \rho_a} \tag{21}$$

$$m_{s,4} = m_c - \int_{t_c}^{t} \frac{2\pi l_c f\rho_g D_{op} Y_{ox,a}}{\ln a - \ln r_c} dt \tag{22}$$

where $t_{s,4}$ is the smoldering time, $m_{s,4}$ is the mass of the cylinder and $\dot{m}_{s,4}$ is the mass consumption rate for case iv. In this case the mass consumption rate and the sample mass vary with r_c, i.e., not explictly with time.

Comparing the experimental and theoretical results a few observations can be made.

The theoretical model predicts a constant mass consumption rate in the drying phase which is not fully verified in the experiments. The drying time increases with larger moisture contents which agrees with theory.

The theoretical pyrolysis consumption rate is almost linear and differs from the parabolic shape seen in the experiments. However if the pyrolysis process is divided in two regions with two different characteristic pyrolysis temperatures then it could yield a reasonable fit to the experiments. The theoretical pyrolysis time is approximately constant, independent of the moisture content, which agrees reasonably well with the experimental results for the pine samples. Nevertheless this is not verified in the embaúba samples, probably due to the simultaneous release of water with volatiles. It should be noted that softwoods in general present a larger fraction of volatiles than hardwood.

The smoldering mass evolution and mass consumtion rate are better fitted by a surface oxidation process with mass tranfer coefficient inversely varying to the diameter, in all cases. That is the smoldering rate is independent of moisture content.

7. Conclusions

An experimental and theoretical investigation of drying, self-ignition, pyrolysis, flaming and smoldering of wood cylinders was made. Pine samples (3 cm diameter and 10 cm length) presented self-ignition for all moisture contents up to 50 % under a specified constant heat flux (2000 W), while embaúba samples presented self-ignition only for samples with moisture contents less than 30 %. This can be possibly explained by the relatively slow release of volatiles or the simultaneous release of water and volatiles in significant levels at these conditions. Most mass is consumed by flaming in pine samples and by drying with pyrolysis in embauba samples. In general, self-ignition and pyrolysis times increased linearly with moisture content. The smoldering process was better described by a process of surface char oxidation with a mass transfer coefficient inversely proportional to the cylinder diameter. Moisture content affected mostly the drying and pyrolysis phases, however it also affects the initial mass and the moment when smoldering starts. Other charcteristics of the burning process could be reasonably described by the theoretical model.

8. Acknowledgement

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