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BURNING OF WOOD SLABS IN A CONICAL CALORIMETER. PART II: EMISSIONS, OXYGEN CONSUMED AND EXHAUST TEMPERATURES

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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. Emissions of CO, CO_2, NO and UHC, oxygen molar fractions and temperatures of exhaust gases from burning slabs ($10\times10\times5$ cm^3) were measured. The combustion behaviour during pre-heating, drying, self-ignition, pyrolysis, flaming and smoldering, for a constant cone calorimeter output of 2000 W, is compared and analysed for slabs with heated surfaces parallel and perpendicular to the wood fibers.*

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.

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.

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).

Nevertheless, there is still a limited amount of data in literature related to the drying, pyrolysis and burning processes of tropical 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, along the vertical/axial direction.

The objective of this work is to analyse the effects of fiber orientation on combustion characteristics of *Pinus elliot*, a common softwood in Brazil, using slabs burned inside a conical calorimeter. Data are presented concerning CO, CO_2, UHC (unburned hydrocarbons) and NO emissions, oxygen fraction and exhaust temperatures from gas products of ovendry square wood slabs (10×10×5 cm^3), burned inside a cone calorimeter with a heat output of 2000 W.

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, and a test workbench were built based on the ASTM E1354–03 standard.

The workbench includes a support structure, hood, radial fan, gas analyzer (Eurotron Greenline 8000), a data acquisition system, gas sampling ring, an ice bath, gas filters, a power control unit, electrical wiring, thermocouples and digital displays of temperature. Figure (1) depicts the cone calorimeter inside the test workbench.

The heater is turned on by a temperature PID controller connected to a thermocouple positioned below the heater, outside the flame zone. The data acquisition system and the continuous gas analyzer are used to register the instantaneous masses, consumption rates and the emissions of CO, CO_2, UHC and NO, the O_2 concentrations in the exhaust gases, slab temperatures, and exhaust gas temperatures. The measurement errors were 5 ppm for CO and UHC, 500 ppm for CO_2 and 1 ppm for NO and O_2.

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

Figure (2) shows a photo of a pinus slab burning in the cone calorimeter.

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 (10×10×5 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, consumption rates, emissions and exhaust temperatures: 3 slabs with exposed surface parallel to the wood fibers and 3 slabs with exposed surface perpendicular to the wood fibers. It should be noted that the presence of heterogeneities, inclusions and resins in the wood can affect significantly the burning characteristics.

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 cone 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.

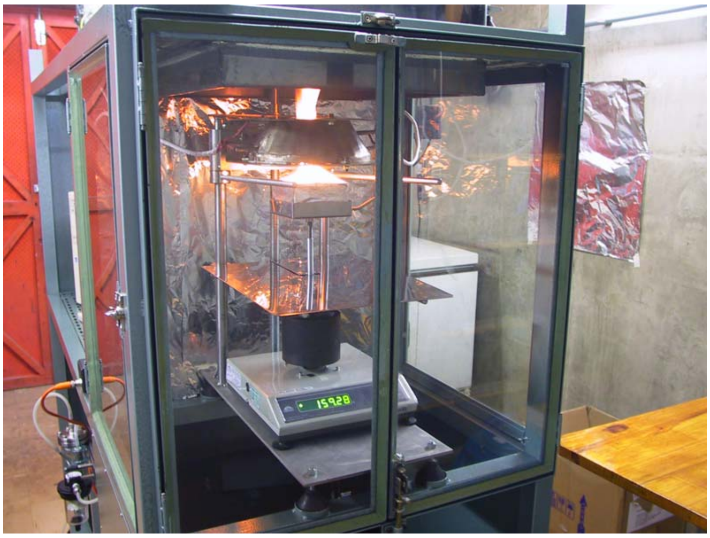

Figure 1 – Burning of pinus slabs in the cone calorimeter.

Figure 2 – Burning of a pinus slab in the cone calorimeter.

5. Results

Figures 3 and 4 present CO_2 emissions, Figs. 5 and 6 present CO emissions, Figs. 7 and 8 present NO emissions, Figs. 9 and 10 present UHC emissions, Figs. 11 and 12 present O2 molar fractions in the exhaust gases and Figs. 13 and 14 present temperatures in the exhaust gases of oven dry pinus slabs for heated surfaces parallel or perpendicular to the wood fibers.

Samples Parallel 1 and Perpendicular 1 did not present early ignition and showed only short periods of flaming at the end of pyrolysis. It can be observed that CO_2 and CO are produced during flaming. The samples which did not ignite early (Parallel 1 and Perpendicular 1) did not present significant formation de CO_2, but showed peaks of CO_2 during the residual flaming. Probably, the presence of resins and inclusions in samples 2 and 3, both with parallel or perpendicular fibers, caused their early ignition. The accuracy of CO_2 emissions were relatively large, 500 ppm, but the periods of significant CO_2 emission could be clearly identified.

The CO emissions are small during flaming and are significant (about 100 ppm) during smoldering, after the flaming period. Samples Parallel 1 and Perpendicular 1 showed large emissions of CO during pyrolysis (mass loss without flaming), probably due to the simultaneous smoldering, and also presented the larger UHC emissions.

It was observed an increase on flame heights just before flame extinction, because the entire slab attained a high temperature with an easier volatile exhaustion caused by surface cracking and enlarging of pores.

The exhaust temperatures of slabs that ignited early followed the mass consumption rate curves, as expected, because the heat release is proportional to the consumed mass. Exhaust temperatures were higher at ignition and at flame extinction and presented constant values during smoldering.

Maximum oxygen consumption occurred during ignition decreased continuously during flaming and was almost insignificant during smoldering.

Additional data concerning mass evolution, consumption rates, percent consumption rates and characteristic times for the samples presented in this paper are given by Costa and Castro (2006).

Table 1 shows the maximum emissions, minimum O_2 molar fractions and maximum exhaust temperatures of all slabs, with fibers parallel or perpendicular to the heating surface. Table 2 shows some data on mass and characteristic times of the slabs, to help to explain the burning behavior.

It should be noted that wood combustion is a complex interplay of physical and chemical processes and non-uniform samples can show different burning characteristics. In the samples studied the peak emissions of gases did not show significant differences, but the exhaust temperatures of samples with perpendicular fibers to the heating surface were higher than the exhaust temperatures of samples with parallel fibers, probably due to the easier release of volatiles.

Table 1 – Maximum emissions, minimum O_2 molar fractions and maximum exhaust temperatures, for slabs with fibers parallel or perpendicular to the heating surface.

Fiber orientation / slab #	Max. CO_2 (ppm)	Max. CO (ppm)	Max. NO (ppm)	Máx. UHC (ppm)	Min. O_2 (molar %)	Max. exhaust temperature (^oC)
Parallel 1	1000	480	6	420	20.8	92
Parallel 2	2000	150	5	110	20.5	95
Parallel 3	3000	130	8	290	20.5	103
Perpendicular 1	1000	550	6	370	20.8	101
Perpendicular 2	3000	150	6	270	20.5	106
Perpendicular 3	1000	520	6	190	20.9	99

Table 2 – Slab mass and time data with different fiber orientations.

Fiber orientation / slab #	m_o (g)	t_{ig} (s)	t_{ep} (s)	dm_p/dt (g/s)	m_{ep}/m_o (%)	m_c (g)	dm_c/dt (g/s)
Parallel 1	173.57	700	2550	0.0471	23.85	26.51	0.009
Parallel 2	180.58	55	2560	0.0549	22.04	19.62	0.011
Parallel 3	184.45	22	2540	0.0566	22.17	23.75	0.009
Perpendicular 1	182.35	2061	3155	0.0408	22.67	30.33	0.010
Perpendicular 2	178.60	57	2650	0.0537	20.58	20.45	0.010
Perpendicular 3	180.37	390	2850	0.0452	24.85	31.83	0,009

m_o = initial mass, t_{ig} = ignition time, t_{ep} = end of pyrolysis time, m_{ep} = mass at end of pyrolysis,
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.

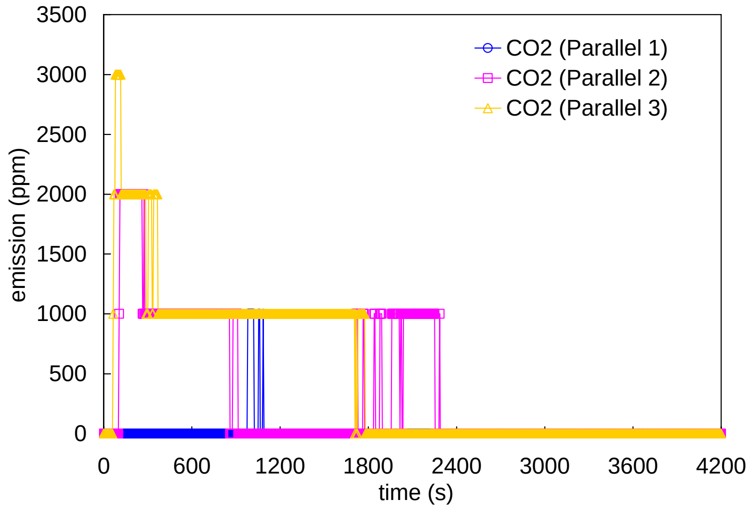

Figure 3 – CO_2 emissions from a burning pinus slabs with fibers parallel to the heating surface.

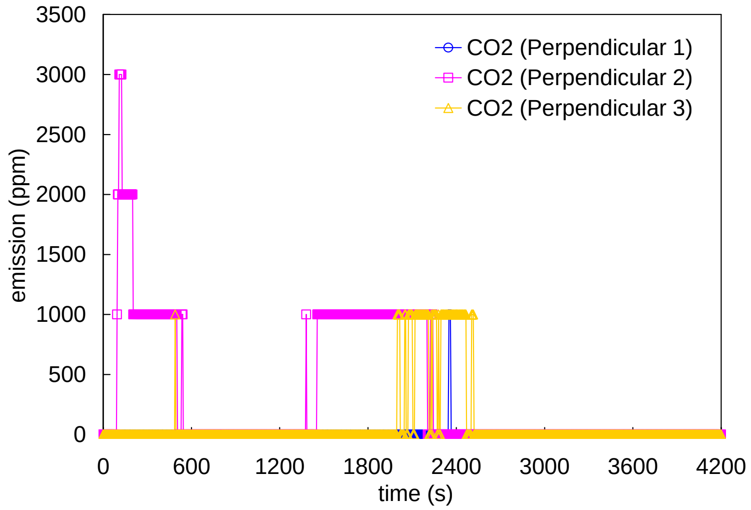

Figure 4 – CO_2 emissions from burning pinus slabs with fibers perpendicular to the heating surface.

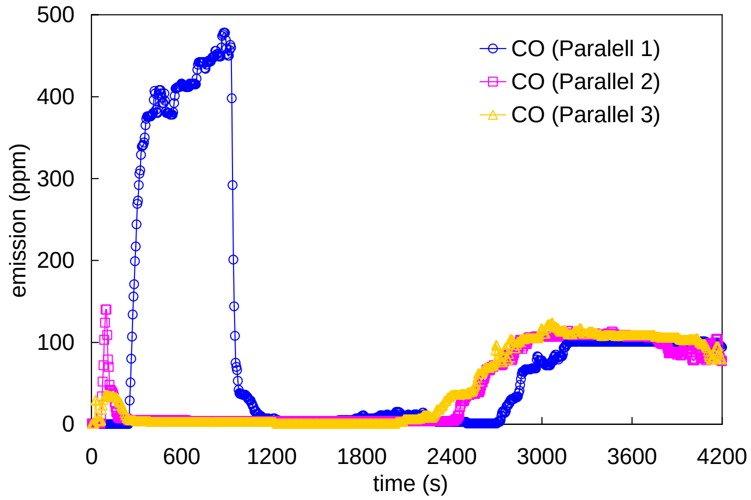

Figure 5 – CO emissions from burning pinus slabs with fibers parallel to the heating surface.

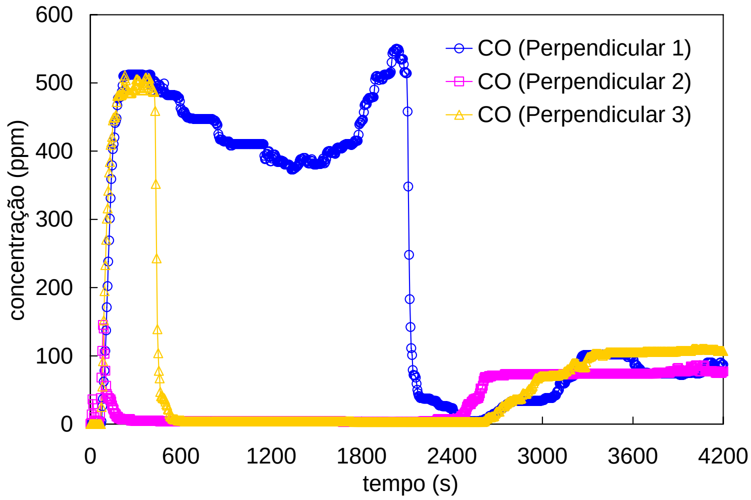

Figure 6 – CO emissions from burning pinus slabs with fibers perpendicular to the heating surface.

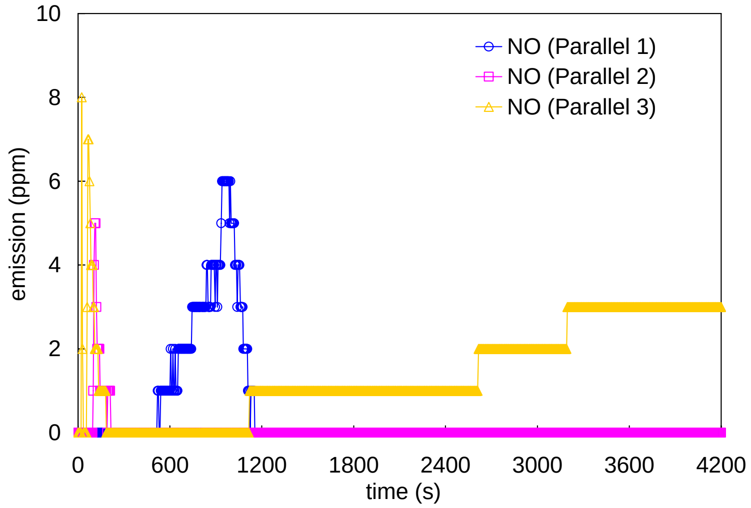

Figure 7 – NO emissions from burning pinus slabs with fibers parallel to the heating surface.

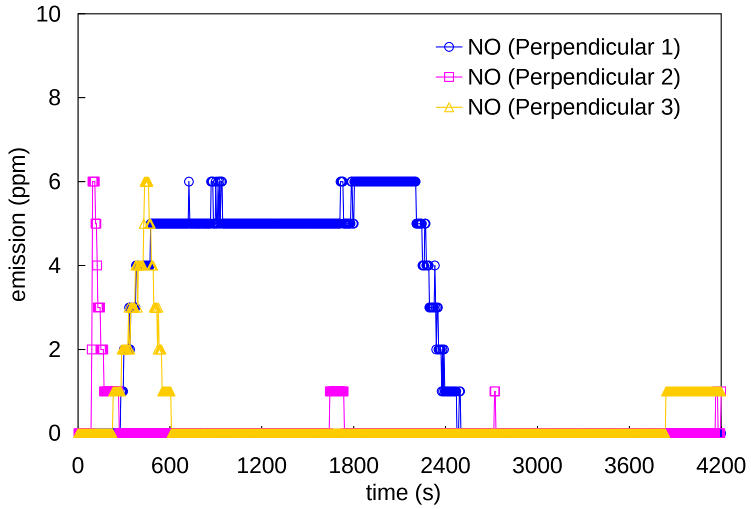

Figure 8 – NO emissions from burning pinus slabs with fibers perpendicular to the heating surface.

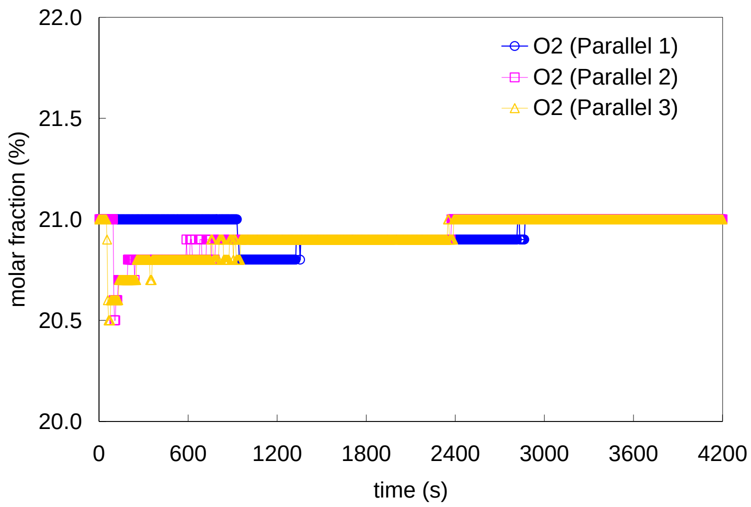

Figure 9 – Molar fractions of O_2 in gases from burning pinus slabs with fibers parallel to the heating surface.

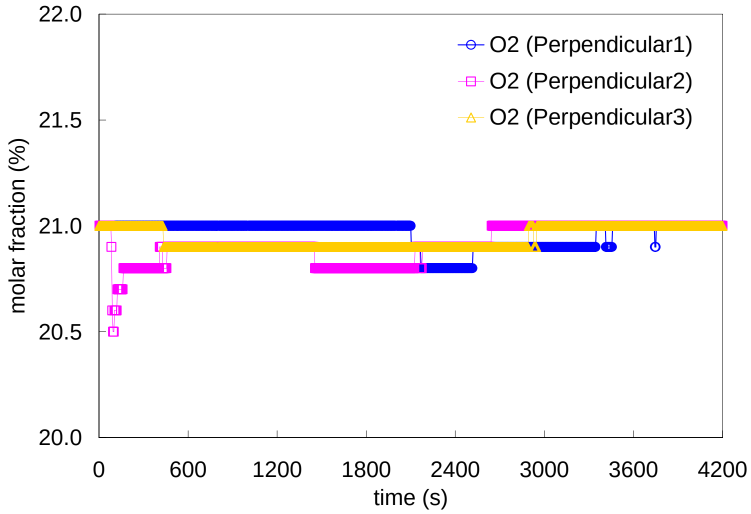

Figure 10 – Molar fractions of O_2 in gases from burning pinus slabs with fibers perpendicular to heating surface.

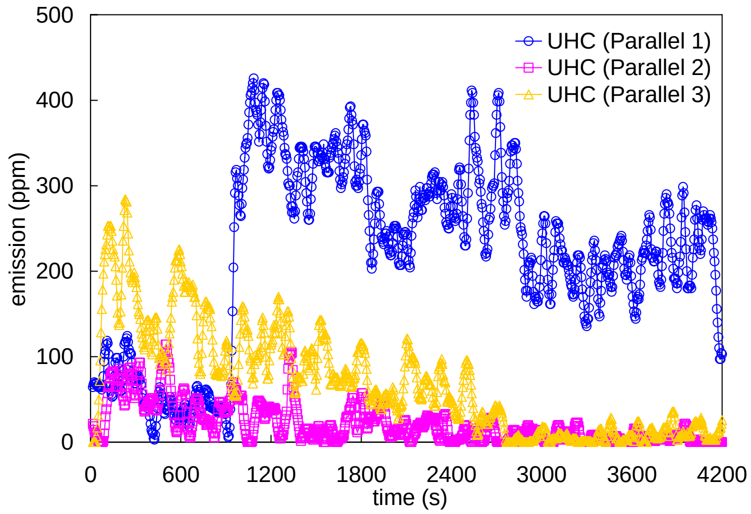

Figure 11 – UHC emissions from burning pinus slabs with fibers parallel to the heating surface.

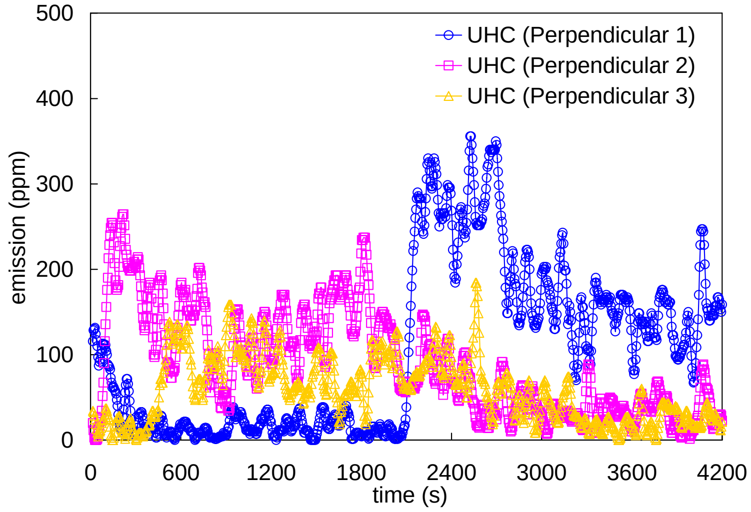

Figure 12 – UHC emissions from burning pinus slabs with fibers perpendicular to the heating surface.

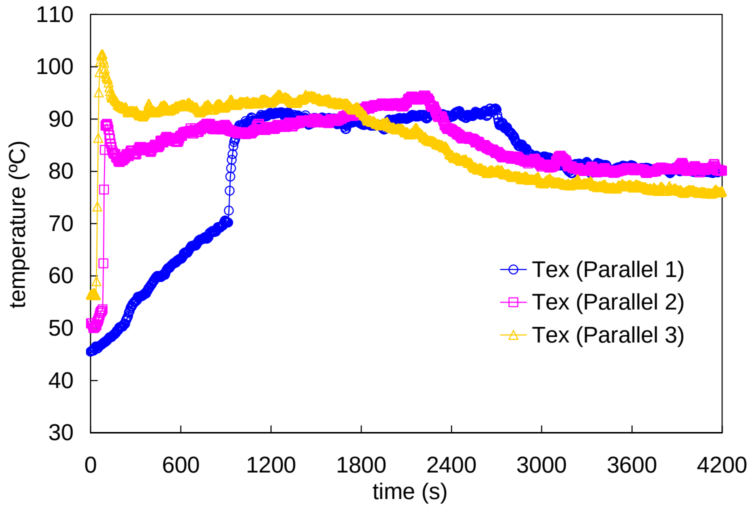

Figure 13 – Exhaust temperatures of gases from burning pinus slabs with fibers parallel to the heating surface.

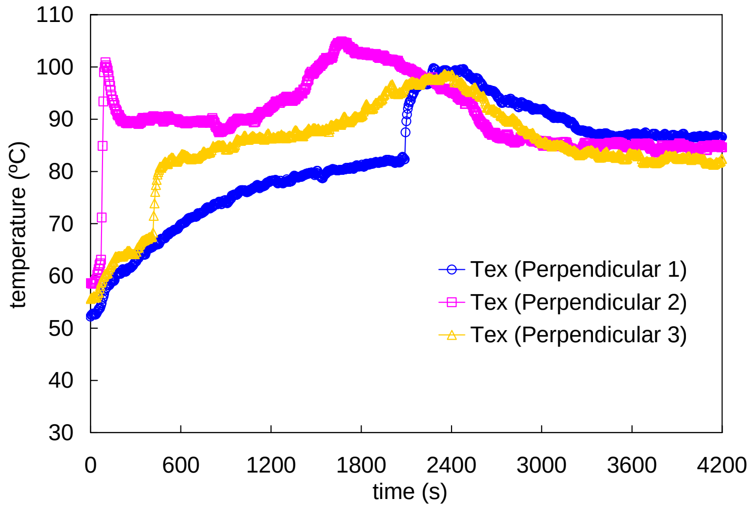

Figure 14 – Exhaust temperatures of gases from burning pinus slabs with fibers perpendicular to the heating surface.

7. Conclusions

The combustion characteristics of slabs of pinus wood (*Pinus elliot*) were studied in a conical calorimeter. Square pinus slabs, 10×10×5 cm^3, were burned with a heater output of 2000 W. The emissions of CO, CO_2, NO and UHC, the oxygen molar fractions and the temperatures of the exhaust gases were measured. The combustion behavior during pre-heating, drying, self-ignition, pyrolysis, flaming and smoldering was compared and analysed for slabs with heated surfaces parallel and perpendicular to the wood fibers. One of the three samples for each fiber orientation did not present early ignition, but presented residual flaming. Flaming characteristics were more uniform and the exhaust temperatures were higher for samples with parallel fibers than for samples with fibers perpendicular to the heating surface. Smoldering characteristics of all samples were similar.

8. Acknowledgement

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