EFFECTS OF DIAMETER AND HEAT FLUX ON BURNING CHARACTERISTICS OF WOOD CYLINDERS

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Abstract. *This work analyses the effects of diameter and heat flux on combustion characteristics of pinus (Pinus elliot) wood cylinders tested inside a cylindrical calorimeter. Cylinders of diameters 15, 20, 25 and 30 mm were tested with a heater output of 2000 W, while cylinders of 30 mm diameter were tested with heater outputs of 1250, 1500, 1750 and 2000 W. Emissions of CO, CO_2 and NOx, exhaustion temperatures, mass evolution, consumption rates, percent consumption rates and characteristic times are presented for the different phases of the combustion process, including drying, pyrolysis, flaming and smoldering.*

Keywords. Combustion, diameter, pyrolysis, emissions, smoldering, cylindrical calorimeter.

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 on burning characteristics of tropical woods 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).

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. Therefore, the objective of this work is to analyse the effects of sample diameter and power input on combustion characteristics of *Pinus elliot*, a common softwood in Brazil, using a cylindrical calorimeter.

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. Experimental Setup

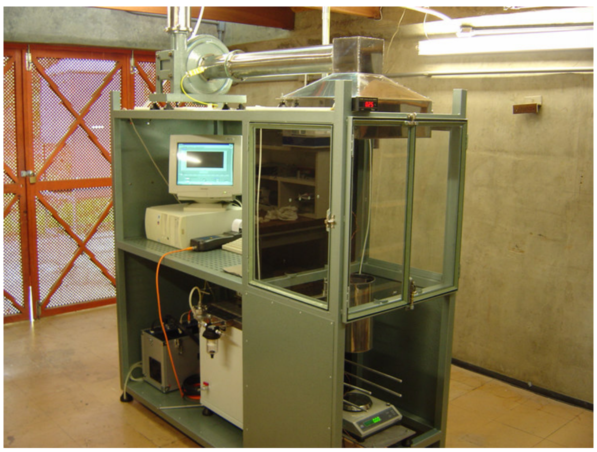
A detailed description of the cylindrical calorimeter used in this study, including sampling, power control and data acquisition systems, is made by Castro (2005). A brief description is presented next.

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

A wood sample was placed on a steel cylinder and this on another support having a disk for air flow rate control, inside the heater. 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. 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) b)

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

3. Sample Preparation and Test Procedure

The sample preparation process and test procedure were described in detail by Castro (2005) and Costa and Castro (2005). Wood cylinders with 10 cm height and different diameters were obtained from pinus wood (*Pinus elliot*), recently cut. The cylinders were machined in the direction of the wood fibers, along the pith.

Tables 1 and 2 show the dry masses of wood samples for the tests of effects of diameter and heat input, respectively.

Table 1. Initial dry mass of *Pinus elliot* samples for tests of diameter variation.*

Diameters	*15 mm*	*20 mm*	*25 mm*	*30 mm*
Mass (g)	8.58	14.15	23.77	26.12
	8.04	14.30	22.57	26.18
	7.77	14.60	22.81	26.56
	7.96	14.92	22.78	-
Average mass	***8.00***	***14.45***	***22.79***	***26.29***
Std. Deviation	***0.35***	***0.34***	***0.54***	***0.24***
% Std. Dev.	***4.33***	***2.37***	***2.36***	***0.91***

* densities of samples with 15, 20 and 25 mm were 22.3 % higher than densities of 30 mm samples.

Table 2. Initial dry mass of *Pinus elliot* samples for tests of power input variation. **

Diameters	*1250 W*	*1500 W*	*1750 W*	*2000 W*
Mass (g)	23.17	23.63	23.90	24.04
	24.85	24.39	24.61	24.67
	24.74	24.77	24.79	24.23
Average mass	***24.25***	***24.26***	***24.43***	***24.31***
Std. Deviation	***0.94***	***0.58***	***0.47***	***0.32***
% Std. Dev.	***3.87***	***2.39***	***1.93***	***1.33***

** all samples have initial diameter 30 mm.

5. Results

Figure (2) shows mass evolution, normalized mass evolution, mass consumption rates (–*dm*/*dt*) and normalized consumption rates (–100*dm*/*dt*/*m*) of dry samples of *Pinus elliot* with different initial diameters and heater power output of 2000 W. Figure (3) shows the same data for dry samples of *Pinus elliot* with initial diameter of 30 mm and heater output of 1250, 1500, 1750 and 2000 W. All data were selected also at 10 s intervals.

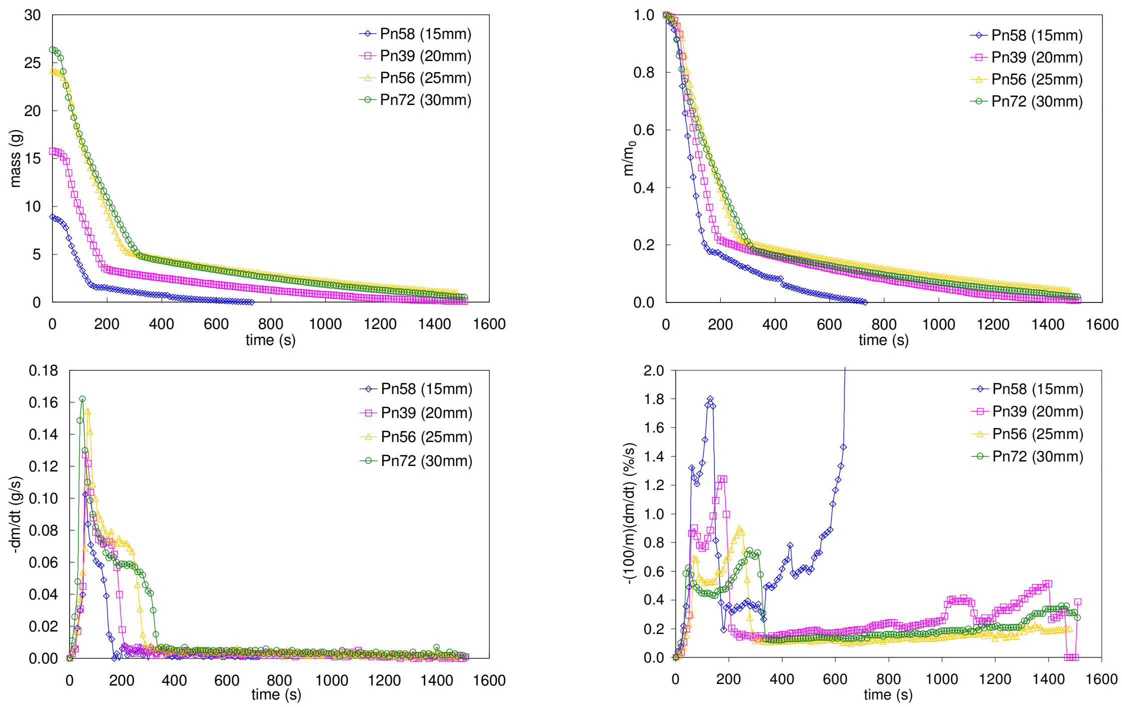


Figure 2 – Mass evolution, normalized mass evolution, mass consumption rates and percent consumption rates of *Pinus elliot* cylinders with 15, 20, 25 and 30 mm diameter under heat input of 2000 W.

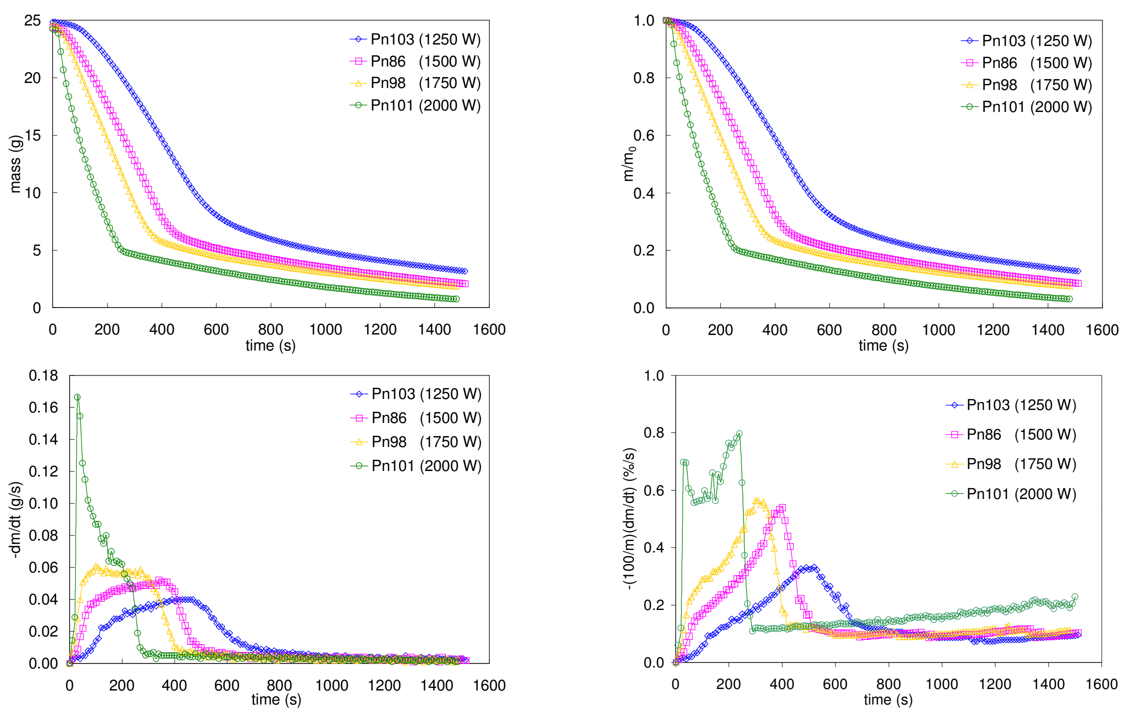


Figure 3 – Mass evolution, normalized mass evolution, mass consumption rates and percent consumption rates of *Pinus elliot* cylinders with 30 mm diameter for power inputs of 1000, 1250, 1500, 1750 and 2000 W.

Figures 4, 5 and 6 show the emissions of CO, CO_2 and NO, respectively, for *Pinus elliot* samples with 15, 20, 25 and 30 mm diameter under heater output of 2000 W.

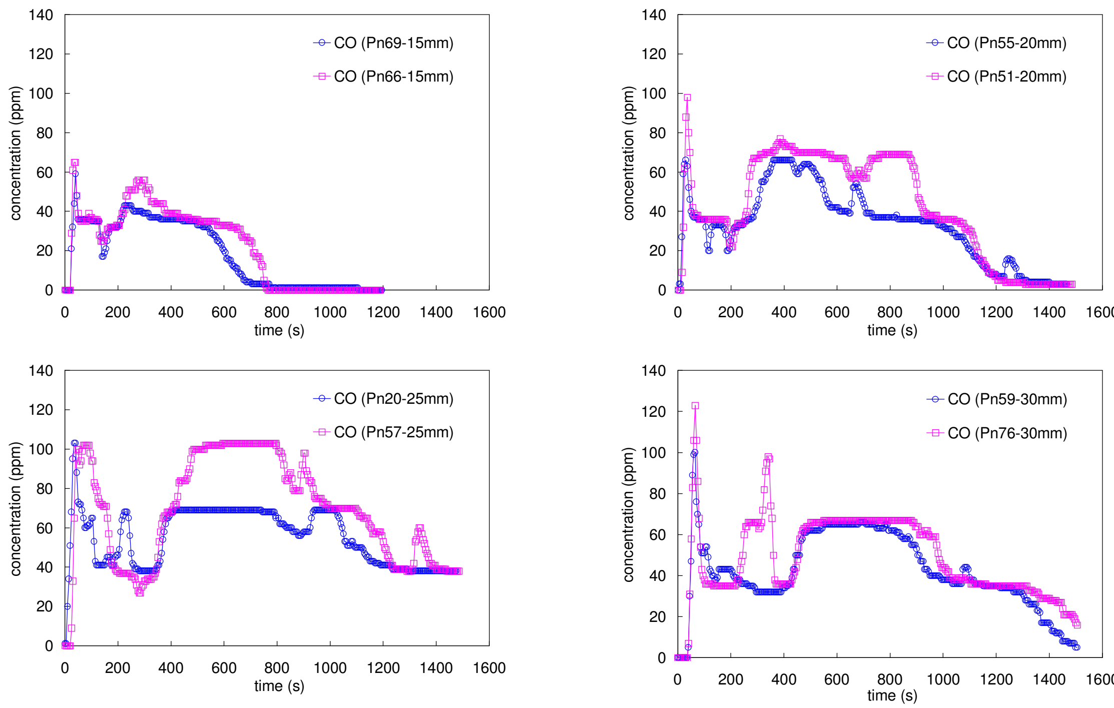


Figure 4 – Emissions of CO of *Pinus elliot* cylinders with 15, 20, 25 and 30 mm diameter burning under 2000 W.

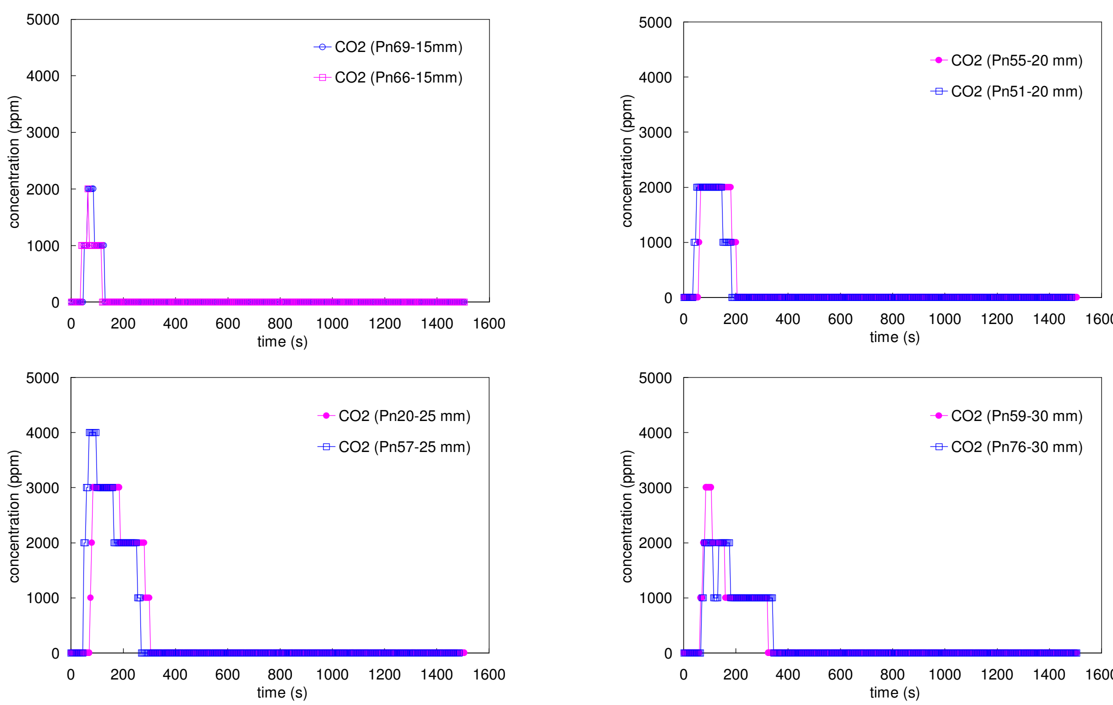


Figure 5 – Emissions of CO_2 of *Pinus elliot* cylinders with 15, 20, 25 and 30 mm diameter burning under 2000 W.

Figures 4 and 5 show that CO_2 emissions are significant during flaming, while CO emissions are more important during smoldering. Emissions of CO and CO_2 increase with diameter, as a consequence of the larger amount of fuel. This tendency was not shown by the 30 mm samples, since they had lower initial densities than other samples.

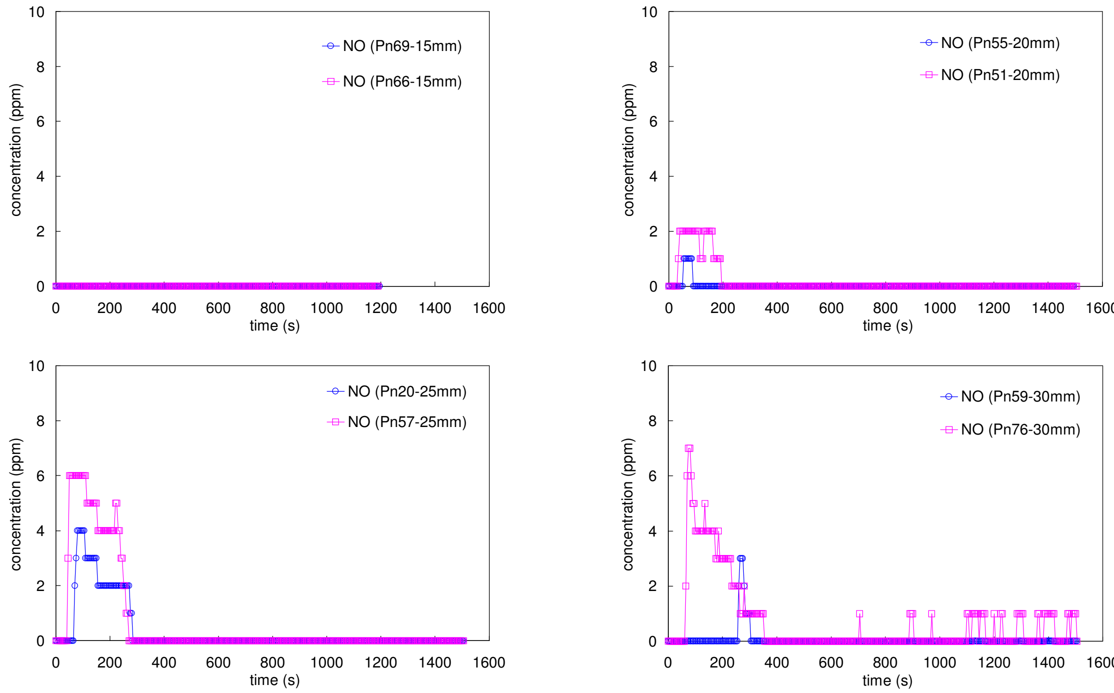


Figure 6 – Emissions of NO of *Pinus elliot* cylinders with 15, 20, 25 and 30 mm diameter burning under 2000 W.

Figures 7 and 8 show the emissions of CO and NO, respectively, for *Pinus elliot* samples with 30 mm diameter for different heater power outputs (1250, 1500, 1750 and 2000 W). CO_2 emissions were negligible, except for heater output of 2000 W, as seen in Fig. 5. Figure 9 depicts the exhaustion temperatures for the same samples of Figures 7 and 8.

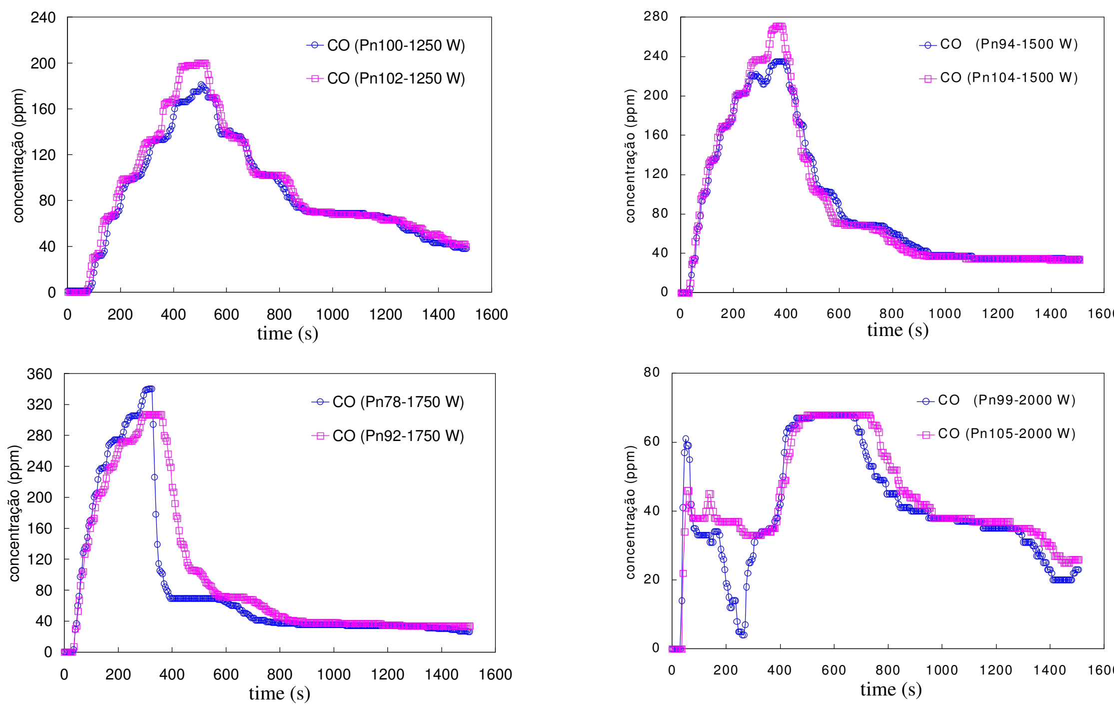


Figure 7 - CO emissions of *Pinus elliot* cylinders with 30 mm diameter for different heater power outputs.

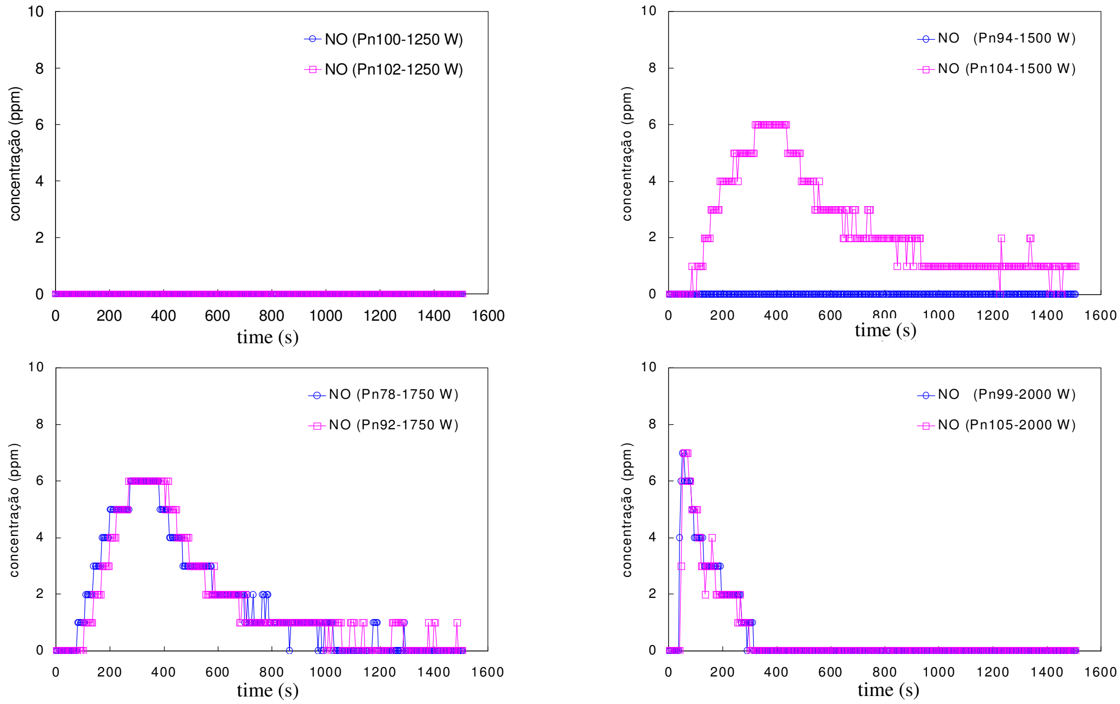


Figure 8 - Emissions of NO of *Pinus elliot* cylinders with 30 mm diameter under different heater power outputs.

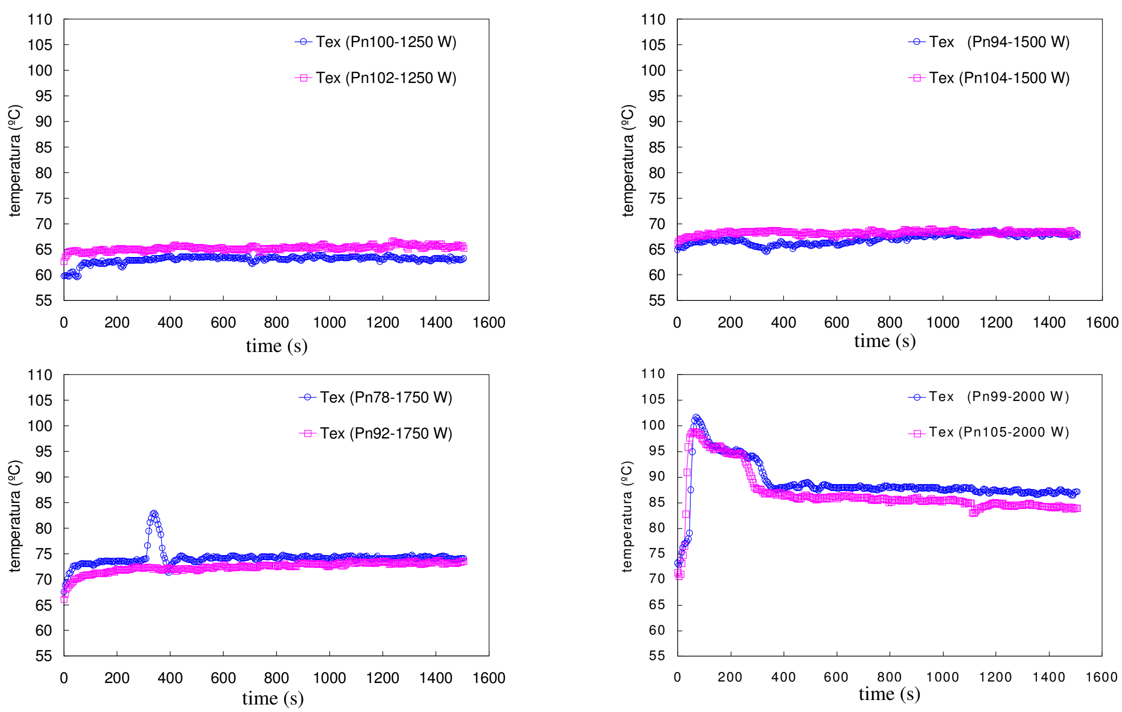


Figure 9 – Exhaustion temperatures for *Pinus elliot* cylinders with 30 mm diameter for different heater power outputs.

Figures 8 and 9 show that peaks of NO emission and exhaustion temperatures increase with increasing power input. Total NO emission is larger for pyrolysis than for flaming. It should be noted that the power input to the samples increases during flaming. CO emissions increased with power input, if there was no flaming.

Figure 10 depicts the effects of diameter on self-ignition times and on times of end of pyrolysis for dry cylinders of *Pinus elliot* with a heater output of 2000 W. Figure 11 depicts the effects of heater power output on self-ignition times (or pyrolysis start) and end of pyrolysis times, with or without flaming, of dry cylinders of *Pinus elliot* with diameter 30 mm.

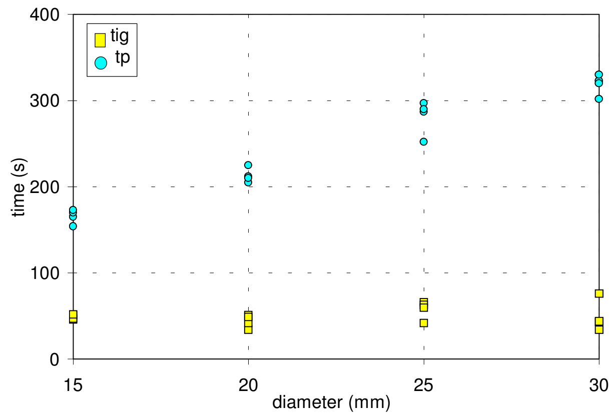


Figure 10 – Effects of diameter on self-ignition times and end of pyrolysis times of dry cylinders of *Pinus elliot* for heater output of 2000 W.

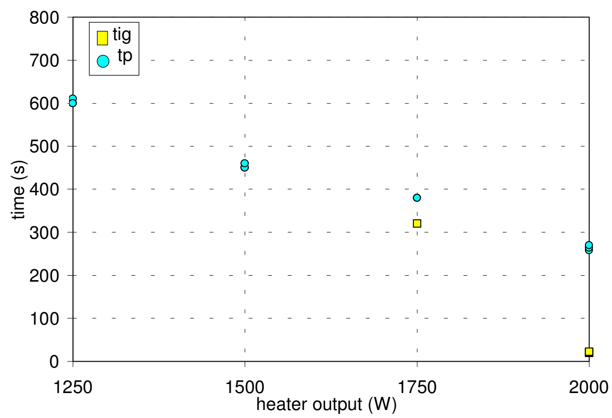


Figure 11 – Effects of heater power output on self-ignition times (or pyrolysis start) and end of pyrolysis times, with or without flaming, of dry cylinders of *Pinus elliot* with diameter 30 mm.

All samples with a heater output of 2000 W presented self-ignition, independently of diameter, as indicated by the initial peaks at the consumption rate curves in Figure 2 and as depicted in Figure 10. It should be noted that the flaming phase ends when the consumption rates are reduced to a small value, approximately constant, corresponding to the smoldering phase. Figure 3 shows that larger samples have larger consumption rates and lower normalized consumption rates during the flaming period. Smoldering consumption rates are slightly higher for samples with larger diameters.

In general, only samples under 2000 W heater output presented self-ignition, as shown in Figure 3, except for one sample with 1750 W, but with a short flaming period, as depicted in Figure 11. As expected, higher heating produces higher consumption rates and higher normalized consumption rates, during pyrolysis or flaming. Smoldering consumption rates are approximately the same for all samples.

Figure 10 shows that the self-ignition times were not significantly affected by diameter, under a 2000 W heater output. End of pyrolysis times increased almost linearly from about 170 s to about 320 s, for diameters varying from 15 mm to 30 mm. Figure 11 shows that the times of end of pyrolysis decrease almost linearly with increasing heater power output, from 600 s to 270 s for powers varying from 1250 W to 2000 W.

7. Conclusions

The effects of diameter and heat flux on combustion characteristics of pinus (*Pinus elliot*) wood cylinders were analysed. Cylinders of diameters 15, 20, 25 and 30 mm were tested with a heater output of 2000 W, while cylinders of 30 mm diameter were tested with heater outputs of 1250, 1500, 1750 and 2000 W. Emissions of CO, CO_2 and NOx, exhaustion temperatures, mass evolution, consumption rates, percent consumption rates and characteristic times were presented for the different phases of the combustion process, including drying, pyrolysis, flaming and smoldering. All samples with a heater output of 2000 W presented self-ignition, independently of diameter. NO emissions increase with increasing power input. CO emissions increase with power input if there is no flaming.

8. Acknowledgement

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9. References

Abu-Said, M.; Atreya, A, Effect of water on piloted ignition of cellulosic materials, *Report NIST GCR-89-561*, 189 p., Gaithersburg, MD, 1989.

Castro, A, Uma Investigação Teórico-Experimental da Combustão de Madeira, *Master Thesis*, INPE, SP, Brazil, 2005.

Castro, A., Costa, F.S., Effects of Moisture Content on Burn Rates and Characteristic Times of Brazilian Woods, *18th International Congress of Mechanical Engineering*, Ouro Preto, MG, Brazil, 2005.

Costa, F.S.,Castro, A., Numerical Simulation of the Burning of Wood Cylinders, *18th International Congress of Mechanical Engineering*, Ouro Preto, MG, Brazil, 2005.

Costa, F.S., Castro, A., Carvalho-Jr. J.A., Burning Characteristics of Wood Cylinders, *17th International Congress of Mechanical Engineering*, São Paulo, SP, Brazil, 2003.

Crutzen, P.J., Andreae, M.O., Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles, *Science*, 250, 1669, 1990.

Di Blasi, C., Branca, C., Sparano, S., La Mantia, B., Drying characteristics of wood cylinders for conditions pertinent to fixed-bed countercurrent gasification, *Biomass and Bioenergy*, v. 25, n. 1, p. 45-58, 2003.

Kanury, A.M., Ignition of Cellulosic Solids: Minimum Pyrolysate Mass Flux Criterion, *Combustion Science and Technology*, Vol. 16, p.89, 1977.

Galgano, A., Di Blasi, C., Modeling the Propagation of Drying and Decomposition Fronts in Wood, *Combustion and Flame*, Vol. 139: 16–27, 2004.

Saastamoinen, J., Richard, J.R., Simultaneous Drying and Pyrolysis of Solid Fuel Particles, *Combustion and Flame*, Vol. 106: 288-300, 1996.

Spearpoint, M.J., Predicting the Ignition and Burning Rate of Wood in the Cone Calorimeter using an Integral Model, Building and Fire Research Laboratory, *Report NIST GCR 99-775*, Maryland, USA,1999.

Spearpoint, M.J., Quintiere, J.G., Predicting the Burning of Wood using an Integral Model, *Combustion and Flame*, 123:308-324, 2001.

Suuberg, E.M., Milosavljevic, I., Lilly, W. D., Behavior of charring materials in simulated fire environments, *Report NIST-GCR-94-645*, 651p., Gaithersburg, MD, 1994.