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EVALUATION OF PAULOWNIA'S BIOMASS IN A PELLETIZED FORM

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Abstract. *This study intends to evaluate* Paulownia*'s biomass in a pelletized form and compare with commercial and ENplus certified Pine pellets. Paulownia is a fast growing and resistant species in a wide range of climate conditions, native from China. The species used in this work is* COT_2 *from Spain,* Paulownia elongata *x* Paulownia fortunei*, which is an interspecific hybrid and not invasive.* Paulownia*'s biomass heating value is in the same range of other biomass species, such as Pine's, but its low pollutant content makes it an interesting study target. Paulownia logs were cut into small pieces and dried in both a solar and an electric greenhouse, then milled and finally pelletized. Throughout all the stages tests were made to know its moisture content. Pellets had 6.3% in wet basis. Quality tests were performed to the pellets to allow comparing with Pine pellets. Pine and* Paulownia *pellets were burned at three nominal thermal loads on a specifically laboratorial prepared boiler: reduced, medium and high. Thermal efficiency and pollutants emissions were obtained in each of the loads.*

Keywords: *paulownia, pellets, combustion, thermal efficiency, pollutants*

1. INTRODUCTION

The energy challenge that the world faces, resides in the balance between three key vectors, referred as 'World Energy Trilemma': energy security, which is primary energy supply efficient management, both from domestic sources as external, reliance in energy infrastructure and energy suppliers capacity to respond to current and future demand; energy equity, characterized by availability and affordable energy prices for the entire population; environmental sustainability, by achieving energy efficiency, both in the perspective of supply as in the demand, and the development of energy supply forms sustained on renewable sources (IEA, 2013).

Energy production has been dominated by fossils combustibles and it is expected that this trend will continue with values about 80% until 2040 (EIA, 2013). However, renewable energy sources have been showing the fastest-growing, about 6.4% per year (BP, 2014). In Portugal, oil is showing a decrease in consumption, from 58.6 to 43.5% between 2005 and 2013, with sources like natural gas (17.2%), coal (12.3%), biomass (13.3%) and electric energy (12,1%) becoming more significant (DGEG, 2015).

Even though fossils have some advantages, such as higher heat value, availability and abundance, its environmental disadvantages have been a recurrent topic for years, in particular due to the great dependence of importers countries and the greenhouse gas (GHG) effect associated with much prejudicial climatic changes. In Kyoto protocol ratification in 2002, countries from all over the world, pledge to reduce GHG emissions in order to mitigate its effects. In the last decades, European Union has revised energy policies on an effort to create a common orientation to member states. These policies purpose is to fulfil environmental goals in a competitive way through a more expressive use of renewable energy sources. In January 2014, European countries have agreed on a 2030 Framework, setting more ambitious goals for this horizon in the 'World Energy Trilemma' context: reduce GHG emissions by at least 40% compared to 1990 levels; increase the share of renewable energy to at least 27%; increase energy efficiency by at least 27% (EC, 2015). Portugal has been presenting a positive trend, result of energy sources diversification, focusing on increasing the use of renewable, such as wind, solar and biomass, and non renewable ones less pollutant, such as natural gas, combined cycled thermoelectric power plants and cogeneration units. Within the energy sector, the one with the most weight in GHG emissions (69.7%), transport (24.7%) and energy production and transformation (25.3%) are the ones with more influence (APA, 2014). GHG emissions have decreased in the last years, especially from 2005, presenting below the maximum limits established in Kyoto protocol for Portugal (APA, 2014).

Currently, one of the most sought out renewable source is biomass, which is a source that has been used for thousands of years. Primary energy consumption from biomass in the world is about 10%, being the 4th source most used (IEA, 2013), only after oil, coal and natural gas (REN 21, 2013). In Portugal, biomass production has been increasing, by 2013, 50% of the renewable energy has origin in biomass, with 11 and 14% influence in primary and final energy consumption, respectively (DGEG, 2015). Biomass combustion has a neutral role in Carbon dioxide balance, since it has been previously absorbed by biomass during its growth, hence its great importance in the environmental context and as an alternative to fossil fuels. According to Tabak (2009), this perspective does not take into account the Carbon dioxide that is emitted in combustion preceding activities, such as production and application of fertilizers, the sowing and harvesting, transport and conversion of biomass or other biofuel type, suggesting that there is still much to consider on this issue. The properties with more influence in biomass combustion are: moisture content, calorific value, fixed carbon, volatiles, ash and cellulose/lignin ratio (McKendry, 2002).

Paulownia, also known as Princess Tree, is a plant from China with very fast growth, in favorable conditions, can reach up to 5 meters in the first year, and uses a highly efficient photosynthesis to fix carbon. Being a short-rotation woody crop, whose species and their hybrids, provide biomass at a higher rate compared to other plants whose lignin composition has a prominent part, enables a more consistent supply due to higher production, reduces storage costs and impairs losses of biomass stored (Zuazo et al., 2013). *Paulownia*'s wood applications are general carpentry, musical instruments, games, crafts, frames and pallets. Due to its strength and lightness, its wood is very suitable for furniture and flooring caravans, aircraft and light vessels. Honey and natural cosmetics can be produced through the flower and leaf, respectively. *Paulownia* hybrids are already used in many countries; the specie used in this work was COT_2, which is a not invasive cross between *P. elongate* and *P. fortunei*, from Spain.

The main purpose of this work was to evaluate *Paulownia*'s biomass as a fuel in a pelletized form, in energy and environmental performance perspective of a domestic boiler and compare the results with the ones obtained with commercial and ENplus certified Pine pellets, also tested. Pine and *Paulownia* pellets were burned in three nominal thermal loads: reduced, medium and high. Data was obtained in order to determine thermal efficiency and, simultaneously, pollutants emissions were monitored in each load.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1 Sample preparation

Paulownia pellets were produced specifically for this work. *Paulownia* logs were obtained from collaboration with *Maderas Alvarez Oroza SL*, a company from Spain. After cutting it into small pieces, they were dried both in a solar and an electric oven. Moisture content was monitored along the drying process. The raw material was ground in a hammer mill, model GKLC-19PK2010, passing through a 6 mm screen. Afterwards, the samples were screened with 1.50 mm amplitude for 10 minutes in the AS200 *Retsch* vibratory sieve shaker, presenting the samples a mean diameter of 827±65 μm. *Paulownia* pellets were produced in a lab AGP GK5500 pelletizer press with a mass feed rate of 51 kg/h. ENplus certified Pine pellets were acquired to *Pinewells*, a Portuguese company. Pellets used in experimental tests are shown in Fig. 1.

Figure 1. *Paulownia* and Pine pellets.

2.2 *Paulownia* pellets characterization

The length and diameter of twenty pellets for each of the three samples were measured with a digital caliper with 0.1 mm precision, according to ÖNORM M7135. The respective mass was determined using the Precisa 6200 precision scale. Using the relation between pellet mass and volume, considering the sample a cylinder (*Rabier et al.*, 2006), particle density was obtained.

Pellets moisture content was established according to EN 14774-2:2009; later on, using a Venticell 50 L oven at a temperature of 105 ± 2ºC pellet samples were dried, until constant mass was achieved. Equation (1) show how the moisture content, in wet basis, was determined.

$$MC_{wb}(\%) = \frac{m_w - m_d}{m_w} \mathrm{x}100 \quad (1)$$

where m_w is the initial wet mass and m_d the dry mass.

To determine mechanical durability, three samples were tested in a tumbling device according to ASAE S269.5:2014. 500 ± 10 g were manually sieved using a 3.35 mm metal wire cloth and then tumbled for 500 rotations in a period of 10 minutes (Temmerman *et al*., 2006). After sieving the sample again, the remaining pellets were weighed. Mechanical durability was calculated with Eq. (2).

$$Durability\ (\%) = \frac{m_{p\_final}}{m_{p\_initial}} \mathrm{x}100 \quad (2)$$

where m_{p_final} represents the pellets mass after tumbling and $m_{p\_initial}$ pellets mass before tumbling.

Paulownia proximate and ultimate analyses were performed by LNEG, a Portuguese certified laboratory. The results are presented in Tab.1, along with Pine physical (Ferreira *et al.*, 2013) and chemical (Pinewell corp.) characterization, uncertainties (Ferreira *et al*., 2014) and respective limits of the ENplus standard.

Table 1. *Paulwonia* and Pine physical and chemical properties, uncertainties and ENplus limits.

	Unit	*Paulownia*	Pine	Uncertainty (%)	ENplus-A1
Length	mm	39.66 ± 0.09	20.9 ± 0.18	0.06	6 or 8
Diameter	mm	6.1 ± 0.03	6.1 ± 0.06	0.37	6 or 8
Mass	g	1.34 ± 0.01	0.75 ± 0.02	0.01	-
Particle density	kg/m^3	1164.3 ± 15.9	1190.8 ± 18.98	0.01	≥ 600
Moisture content (wb)	%	6.2 ± 0.9	5.9 ± 0.2	0.26	≤ 10
Mechanical durability	%	98.7 ± 0.6	99.2 ± 0.058	0.03	≥ 97.5
Ash	% (m/m)	1.2	0.68	-	≤ 0.7
Volatile	% (m/m)	82.9	-	-	-
Fixed Carbon	% (m/m)	15.9	-	-	-
Total Carbon	% (m/m)	49.1	50.6	-	-
Hydrogen	% (m/m)	6.0	6.4	-	-
Nitrogen	% (m/m)	<1.0	<0.005	-	≤ 0.3
Sulfur	% (m/m)	0.031	0.01	-	≤ 0.03
Chlorine	% (m/m)	0.023	<0.005	-	≤ 0.02
Oxygen	% (m/m)	43.6	42.9	-	-
LHV	MJ/kg	18.30	18.79	-	16.5 ≤ LHV≤ 19

2.3 Experimental methodology

The 20 kW nominal thermal boiler used in this work was an Aqualuxo model, from the Portuguese company *METLOR*, which had about 35 kg pellets capacity. The feeding occurs by the top, through an intermittent screw, in which operation/pause time defines the thermal input. To start the combustion a part of the pellets, in contact with an electric resistance, causes the ignition and flame propagation occurs throughout the pellets and air mass. The energy generated during combustion promotes the heating of the water circulating in the heat exchanger tubes and the ambient air. The ashes generated during the process are dragged from the side walls to a removable tray by action of the supplied air. The exhaustion of combustion gases was made through the laboratory exhaustion system, which was turned on during the initial minutes of each test and shut off only when the test finished. The installation scheme and boiler photo is shown in Fig. 2.

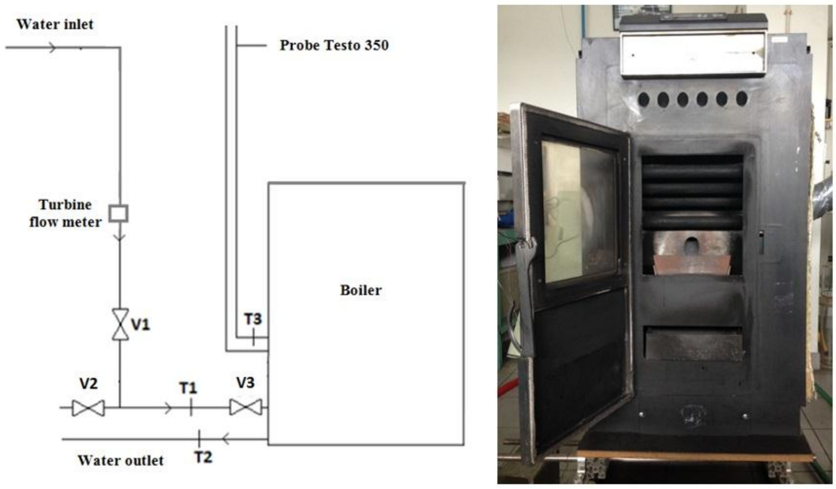

Figure 2. Installation scheme and boiler photo.

2.4 Performance calculations

The measurement of water inlet and outlet and flue gases temperatures was performed with K type thermocouples, *T*1, *T*2 e *T*3, respectively, connected to a TC-08 data logger linked, via USB, to Picolog Recorder. Through a turbine flow meter, the water mass flow rate was measured by connecting the meter to a NI USB-6008 DAQ data logger, which transmitted the signal to National Instrument LabVIEW 8.6. Pellets initial and final mass in the hopper was weighed in a scale, 6200 D model by Precisa. The pellets mass flow rate was obtained by the ratio between the mass difference and the time interval of the test. Exhaust gas composition was monitored with a 350 Emission Analyzer connected to software Easy Emission, both from Testo: oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NO_x). Values were corrected to a common base @ 13% O_2.

The boiler thermal efficiency was determined by Eq. (3).

$$\eta(\%) = \frac{\dot{Q}_{output}}{\dot{Q}_{input}} = \frac{\dot{m}_{H_2O}\ x\ \bar{c}_{H_2O}\ x\ (T_{out} - T_{in})}{\dot{m}_p x\ LHV} \tag{3}$$

where $\dot{m}_{H_2O}$ is the water mass flow rate (kg/s), $\bar{c}_{H_2O}$ the liquid water specific heat (kJ/kg·K), T_{out} and T_{in} the outlet and inlet water temperatures (ºC), respectively, $\dot{m}_p$ the pellets mass flow rate and LHV the species lower heating value (kJ/kg).

2.5 Uncertainities

Uncertainty average values for the three loads, calculated according to Coleman and Steele (2009), associated to the process of measuring the critical variables for this study are presented in Tab. 2.

Table 2. Variable measurement uncertainties

Variable	U (%)		Variable	U (%)
O_2 emission	0.2000		Water inlet temperature	4.77
CO emission	0.0140		Water outlet temperature	2.90
CO_2 emission	0.3725		Exhaust gases temperature	1.21
NO emission	0.0005		Pellets mass flow rate	0.03
			Water mass flow rate	2.24

3. RESULTS AND DISCUSSION

Before initiating the tests the heat exchanger was cleaned and tested by the manufacturer in order to assure maximum possible heat transfer from the combustion chamber to the water running through the heat exchanger.

The tests were made in reduced (r), medium (m) and high (h) load. The results represent the average of three tests for Pine and one for *Paulownia*, due to low material availability, and are presented in Tab.3.

Table 3. Boiler experiment results for each load

		Thermal input (kW)	Fuel mass flow rate (kg/s)	Thermal Efficiency (%)	CO (ppm dry volume)	CO_2 (% dry volume)	NO_x (ppm dry volume)	Exhaust gases temperature (ºC)	Exhaust gases heat losses (kW)
Pine	r	6.01	1.15	50.06	3485.18	7.16	45.27	115.67	2.54
	m	9.66	1.85	57.89	1248.28	7.22	67.89	177.41	3.41
	h	17.68	3.39	64.44	201.71	7.37	78.52	287.01	5.89
Paulownia	r	5.70	1.12	51.58	4865.27	7.04	173.41	137.26	2.25
	m	9.13	1.80	64.13	1558.89	7.00	171.02	210.94	2.54
	h	15.57	3.06	66.30	1535.65	7.19	151.79	284.67	5.04

3.1 Effect of fuel mass flow rate

Tests were performed with Pine and then with *Paulownia*. Initially, due to *Paulownia* pellets higher length, the flow rate was lower, as the volumetric feed screw is dependent of the pellets dimensions. That lower mass flow rate induced lower combustion efficiency and did not allow comparing results between the two species. To overcome this obstacle, after a series of unsuccessful attempts to approximate the mass flow rate by changing the screw operation/pause time, pellets were broken into approximately 20 mm length units, a value closer to those made of Pine.

Figure 3 shows the effect of pellets mass flow rate in boiler efficiency.

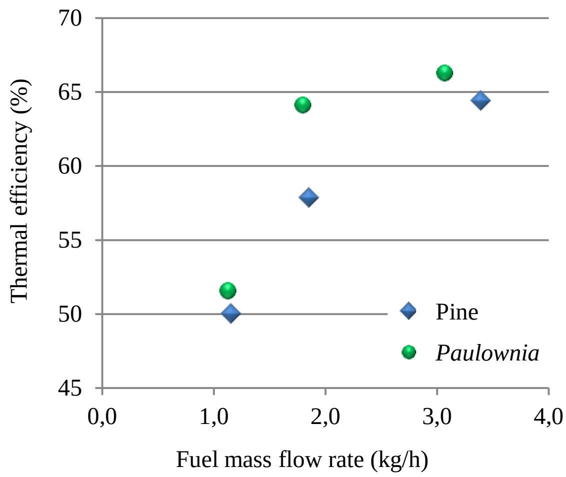

Figure 3. Fuel mass flow rate effect in boiler thermal efficiency.

Fuel mass flow rate has an impressive influence in boiler's thermal efficiency, increasing by 14 percentage points for Pine and 15 for *Paulownia,* when comparing reduced with high load. *Paulownia* pellets attained a thermal efficiency higher to Pine pellets by 1.5, 6.0 and 1.9 percentage points, in reduced, medium and high load, respectively. None of the species fulfills the minimum limits required by EN 14785:2006 standard (70 and 75% in reduced and high load, respectively).

One should bear in mind that these results are based on the boiler manufacturer's setup for the different loads. It is possible that altering that setup would result in different performance values, especially concerning excess air reduction that, to a certain extent, would increase thermal efficiency.

Figure 4 shows the effect of pellets mass flow rate in oxygen and excess air, measured in the flue gases in approximate stationary periods.

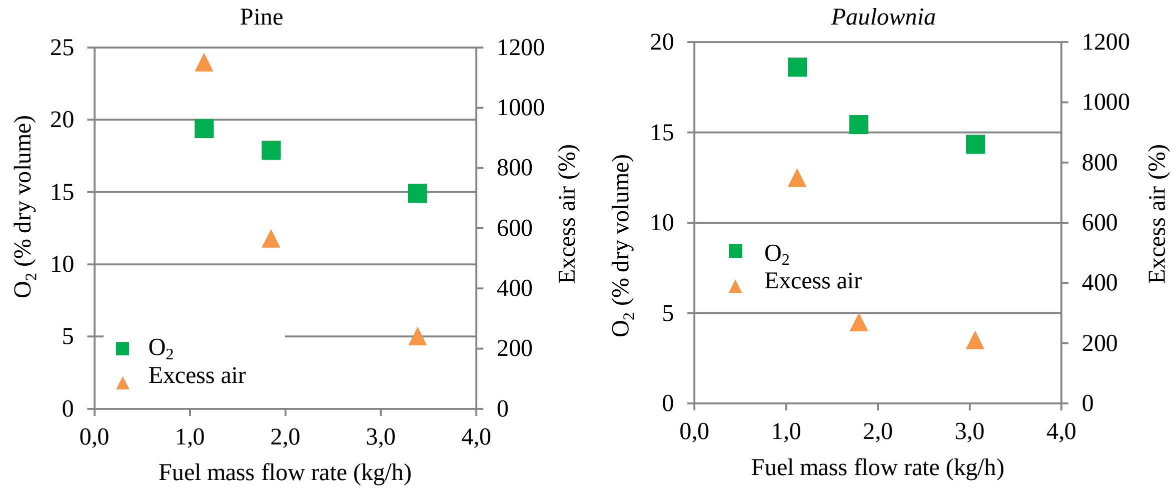

Figure 4. Fuel mass flow rate effect in oxygen and excess air.

Oxygen and excess air exhibit a decrease as the mass flow rate increases both in Pine and in *Paulownia*, which is related to the fact that the boiler does not adjust the air mass flow rate to different fuel loads. The amount of air supplied to the combustion increases in each load, not enough however to meet the increase of the fuel mass flow rate. Thus, with more fuel and less air, the combustion temperature rises and the excess air decreases.

The influence of the fuel mass flow rate on CO, CO_2 and NO_x emissions in approximate stationary periods is presented in Fig. 5.

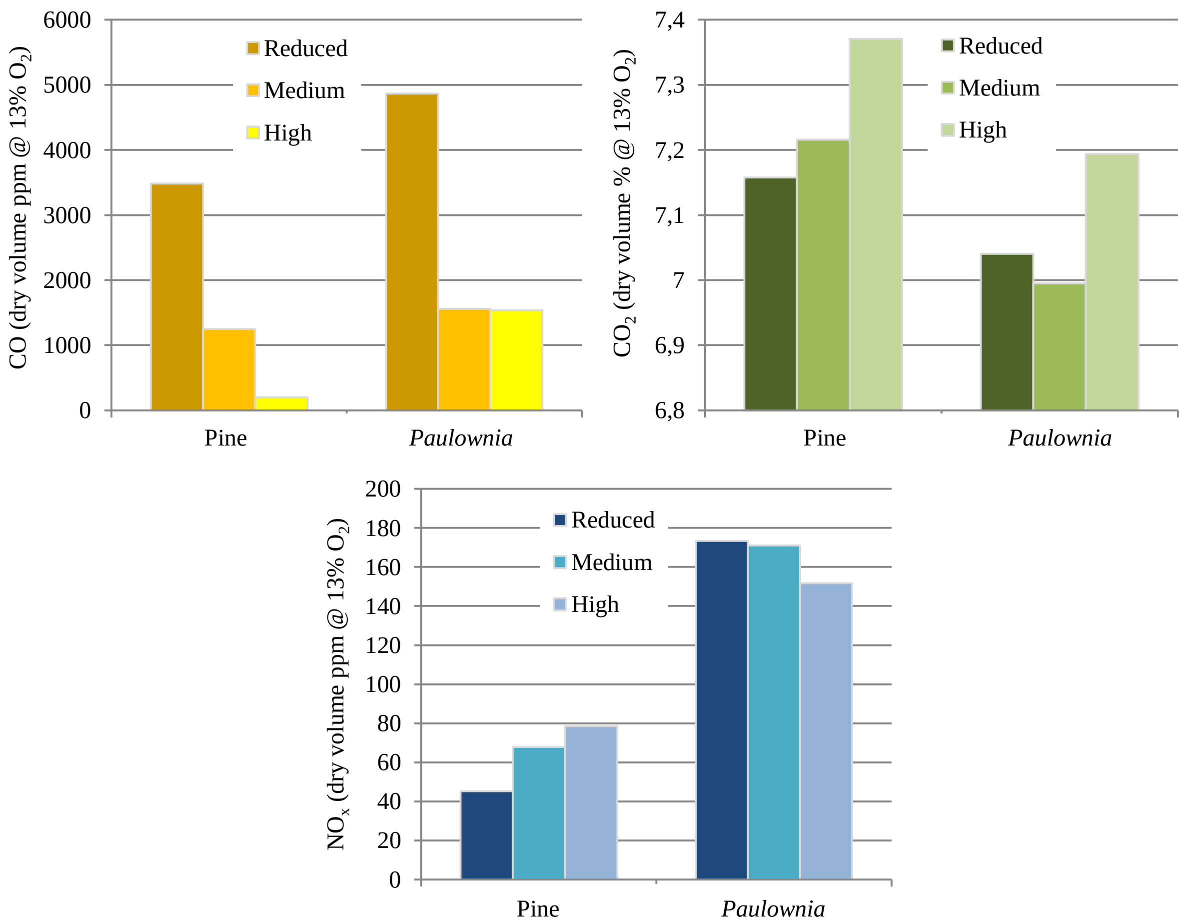

Figure 5. Fuel mass flow rate effect in CO, CO_2 and NO_x emissions.

CO concentrations decrease with the increase of the pellets mass flow rate. *Paulownia*'s emissions are higher than Pine's 1.4, 1.2 e 7.6 times in reduced, medium and high load, respectively. *Paulownia* shows a less pronounced reduction in high load than Pine, probably influenced by the smaller mass flow rate, which caused a decrease in temperature since the exhaust gas temperature shows a somewhat lower value than Pine's, which never took place with the other loads, as shown in Tab.3, and consequently in excess air, impacting greatly CO emissions. Only Pine CO emissions in high load comply with the maximum limits, 600 and 400 ppm @13% O_2 for reduced and high load, respectively, required by EN 14785:2006 standard.

Fuel mass flow rate does not have much influence in CO_2 emissions; they are, however, lower in *Paulownia* pellets. High CO emissions and, consequently, low CO_2's indicates a low combustion quality which influences the process efficiency (Fig. 3).

Even though *Paulownia* and Pine NO_x trend is opposed, emissions do not vary much with the fuel mass flow rate. NO_x formation can be caused by three mechanisms, fuel, thermal and prompt, but since the last two occur in higher temperatures (1300 ºC) and richer mixtures (Loo e Koppejan, 2008) the fuel-NO_x mechanism is probably accountable for the respective emissions. The major difference is between the values of the two species: *Paulownia* emissions are in average 3.8, 2.5 and 1.9 times superior to Pine; *Paulownia* higher values were expected due to its superior content of nitrogen (Tab. 1).

3.2 Poluttant emission

Figure 6 shows the influence of excess air in CO, CO_2 and NO_x emissions in approximate stationary period.

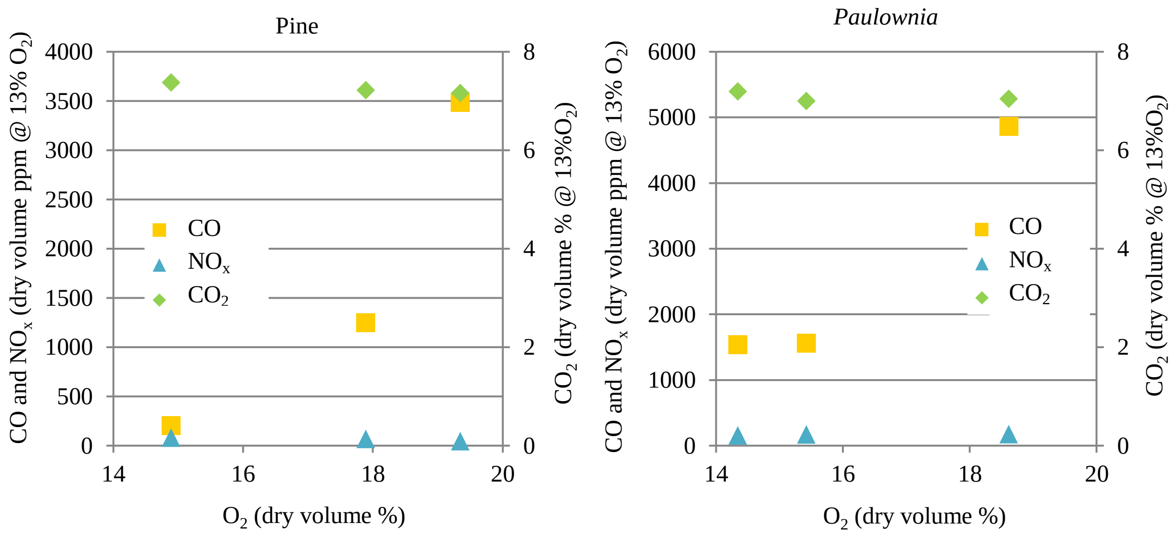

Figure 6. Oxygen effect on CO, CO_2 and NO_x emissions

Literature reports that excess air, from which directly depends O_2 availability in combustion, is the factor that influences the most CO emissions (Loo and Koppejan, 2008). High CO emissions result from combustion low temperatures, inefficient fuel and air mixture and short residence time of the flammable mixture in the combustion chamber.

Similar to fuel mass flow rate, the effect of O_2 on CO_2 and NO_x emissions is not significant. CO_2 is more dependent on how existent carbon in the fuel converts to both CO and CO_2, influenced by exceedingly low or high excess air values. NO_x is influenced by fuel-NO_x mechanism. The same trend of results was found in Ferreira *et al.* (2013), a previous study performed in the same boiler and in a similar experimental setup. Differences reside in a pronounced decrease of CO emissions in high load for the two species analyzed in that study and higher NO_x emissions for *Cytisus multiflorus*in comparison with *Paulownia*.

4. CONCLUSIONS

This study aimed to evaluate *Paulownia*'s biomass in a pelletized form and compare with commercial and certified ENplus Pine pellets. Both pellets species were burned in a domestic boiler in three nominal loads and the effect of fuel mass flow rate and excess oxygen was observed.

Boiler thermal efficiency was greatly influenced by higher fuel mass flow rate, increasing from 50.1 to 64.4% in Pine and 51.6 to 66.3% in *Paulownia*, presenting this last species the highest values in every test. Nonetheless, both species do not meet the minimum requirements imposed by EN 14785:2006 standard (70 and 75% in reduced and high load, respectively).

CO emissions have a conversely proportional relation with fuel mass flow rate and a proportional relation with O_2 for both species; *Paulownia*'s are much higher, however, about 1.4, 1.2 e 7.6 times than Pine's, respectively, in reduced, medium and high load. The greater difference in high load was due to a much lesser pronounced decrease of *Paulownia* CO emissions when compared to Pine's, due to a lower temperature in the combustion chamber caused by the smaller fuel mass flow rate, influencing excess air and consequently, CO emissions. None of the species meets EN 14785:2006 standard requirements in reduced load (600 ppm @13% O_2) but in high load (400 ppm @13% O_2) Pine does.

CO_2 is not influenced by fuel mass flow rate or O_2, being CO high emissions an influence on low CO_2's, which is a good reflection of the boiler low efficiency. *Paulownia* emissions are higher in all tests.

Both fuel mass flow rate and O_2 have a reduced impact on NO_x formation, being the nitrogen content in the fuel, through the fuel-NO_x mechanism, the most important aspect. In this sense, it was possible to confirm that *Paulownia*, whose emissions were higher than Pine's, has higher nitrogen content.

Regarding exhaust gas heat losses, for both species, it increases with increasing fuel mass flow rate due to higher temperatures promoting higher losses. Pine values are higher than *Paulownia*'s.

Paulownia's has a higher growth rate than Pine's which gives that species an interesting potential in terms of availability, which is one of the limiting characteristics of biomass. Considering the resulting higher thermal boiler efficiency, it can be considered an alternative biomass source for the pellets industry, even though more studies are need in order to achieve lower CO emissions in the burning process.

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