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Performance Assessment of Invasive *Acacia dealbata* as a Fuel for a Domestic Pellet Boiler

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The use of alternative energy sources becomes ever more important due to the necessity to minimize the energy consumption of fossil fuels and fight climate changes. This study evaluates the combustion and emissions characteristics of a commercial wood pellet boiler with a nominal thermal output of 20 kW using purposed-manufactured *Acacia dealbata* pellets. Previously, the boiler was tested burning commercial Pine pellets that were used to benchmark the Acacia pellets. The thermal efficiency and emissions of the invasive species pellets were compared at three different predefined operation loads. The efficiency of the boiler was determined using the direct method. The obtained results show that, for the same fuel mass flow rate, the best boiler efficiency was always achieved with Pine pellets. Nonetheless, invasive species pellets deserve some credit if the boiler combustion conditions are adopted to that specific type of fuel. Concerning emissions, CO and NO_x resulting of burning *Acacia* pellets were significantly higher than burning Pine pellets. Overall, the type of pellets had a significant effect on the boiler performance, mainly on emissions.

1. Introduction

The development of societies, industrialization and population growth that has been seen in recent years, triggered a sharp increase in worldwide energy consumption (Lee et al., 2007). During decades fossil fuels were clearly the main support for worldwide energy needs, and currently they continue to be the main source of energy. However, it is expected than in the next 40-50 y, this source of energy will be depleted (Saidur et al., 2011). Furthermore, these fuels are associated with higher emissions of carbon dioxide into the atmosphere, causing irreversible effects on the environment. An even greater effort has been made to increase the consumption of renewable energy, however, there is still much to do regarding energy efficiency and reduction of environmental impacts (González et al., 2006).
There has been an increasing interest in the use of biofuels for energy purposes, driven mostly by political, social and environmental factors. Specifically, the use of biomass will allow countries like Portugal, which do not have its own fossil fuels reserves, to reduce its dependence on imported oil, creating employment through exploration of this fuel and reduce emissions of greenhouse gases (Van Loo and Koppejan, 2008). The combustion of biomass is considered carbon neutral, because it does not contribute to CO_2 emissions. During the combustion of biomass it is released the same amount of carbon dioxide that was stored by the plant during its growth (Klason and Bai, 2007). In general way, biomass presents some disadvantages in its use as a fuel. The high moisture content, irregular shape, low bulk density and energy density are some of the reasons why its transport, handling, storage (Kaliyan and Morey, 2009) and combustion are complicated (Mediavilla et al., 2009). Transforming this bulky biomass material into a denser one (pellets) would improve its handling properties as well as reduce transportation and storage costs (Mani et al., 2006).
In Portugal, about 80 % of the raw material used in the pellets production derived from Pine (ANPEB, 2013). In the last few years the total area occupied by Pine has been significantly reduced (INCF, 2013) which leads to concerns of availability of raw material for the pellets industry.
The genus *Acacia* includes about 1,200 species, native mainly from Australia, but also from other regions of the world, such as Africa (Marchante, 2001). Specifically, *Acacia* dealbata Link is indigenous to the Southeast of Australia and was introduced in Europe in 1790 as an ornamental plant, being later planted in

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several areas of southern Europe that by presenting favorable climates led to its strong growth (Sheppard et al., 2006). This species have a number of properties that make it highly invasive, such as, the ability to fix nitrogen, allowing it to live in nutrient-poor environments, its fast growth and the creation of a large amount of seeds which have a high longevity (Sheppard et al., 2006). Currently, *Acacia* is considered an environmental problem and is one of the most abundant invasive species in Portugal, Spain, France and Italy (Lorenzo et al., 2010). Portuguese legislation (DR 565, 1999) refers *Acacia dealbata* as an invasive, and its cultivation is completely prohibited.

However, the use of biomass as fuel for different types of boilers does not avoid pollutant emissions (Stoppiello et al., 2014) and the emission of particulate matter is still a main concern (Migliavacca et al., 2014).

The main purpose of this work is to evaluate the use of *Acacia dealbata* as a fuel for domestic pellet boilers. The obtained results were compared with those obtained with previously tested commercial Pine.

2. Materials and experiments

2.1 Sample preparation

For the present work, two different types of pellets were used: *Pinus pinaster* and *Acacia dealbata*. Pine pellets were acquired from a Portuguese company and they are currently commercialized in Portugal. *Acacia* pellets were manufactured specifically for this work. For this, *Acacia dealbata* was collected in a local forest and dried in a solar kiln, with the moisture content monitored. The drying process was carried out in the summer and took four days. Afterwards, a GKLC-19PK2010 hammer mill grounded the raw material and its products output passed through a 4 mm screen. The mean diameter of the samples was 543 ± 38 μm, after being screened in an AS200 Retsch shaker. Each sieving was made for 10 min with 1.50 mm amplitude. Pellets of *Acacia dealbata* with 6 mm diameter were produced in an AGP GK5500 pelletizer press with a mass feed rate of 77 kg/h.

2.2 Pellets characterization of *Pinus pinaster* and *Acacia dealbata*

Aiming at comparing experimental pellets characteristics some tests were carried out. According to ÖNORM M 7135, the diameter and the length of twenty pellets for each sample were measured using a digital caliper with 0.01 mm precision. The corresponding mass was determined using a precision lab scale, Precisa 6200. The particle density of the pellets was determined using the stereometric method (the ratio between pellet weight and pellet volume), calculating the volume considering them as cylinders (Rabier et al., 2006). The moisture content of pellets was determined according to EN 14774-2 (2009), the pellet samples were dried in a Venticell 50L oven at a temperature of 105 ± 2 °C, until constant mass was achieved. The moisture content, wet basis, was determined according to Eq (1):

$$MC_{wb}\,(\%) = \frac{m_w - m_d}{m_w} \times 100 \qquad (1)$$

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

Table 1: Characteristics of the experimental pellets

	Pinus pinaster	*Acacia dealbata*	Uncertainty (%)
Diameter (mm)	6.15 ± 0.06	6.33 ± 0.19	0.16
Length (mm)	20.9 ± 0.2	20.49 ± 4.52	0.05
Mass (g)	0.755 ± 0.02	0.595 ± 0.16	18.8
Particle density (kg/m^3)	1190.8 ± 19.0	923.6 ± 142.2	13.2
Moisture content (% wb)	5.9 ± 0.21	7.56 ± 0.14	0.26
Mechanical durability (%)	99.2 ± 0.06	86.0 ± 0.8	0.03

Tests of mechanical durability were made for three samples of each type of pellets, using a tumbling device defined by ASAE S269.4 (1998). Thereby, a 500 g sample was manually sieved with a 3.35 mm round hole sieve and then tumbled for 500 rotations during 10 min (Temmerman et al., 2006). The sample was sieved again and the pellets remaining in the sieve were weighed. The mechanical durability was determined according to Eq (2):

$$\text{Durability}\,(\%) = \frac{\text{Mass of pellets after trumbling}}{\text{Mass of pellets before trumbling}} \times 100 \qquad (2)$$

The characteristics of the pellets used in the tests are shown in Table 1.

The obtained results show some differences between the physical properties of commercial Pine pellets and the pellets made of Acacia dealbata. Mass, particle density and mechanical durability were those presenting the highest differences. Regarding the dimensions, both pellets show some similarities. Acacia pellets had a higher moisture content (see Table 1), but below the 10 % established by EN 14961-2 (2011). The mechanical durability achieved with Acacia pellets was nonetheless below the minimum established for the same standard, 97.5 %.

2.3 Experimental setup

The boiler used in the tests was a METLOR Aqualux, a commercial 20 kW nominal thermal output unit. It is composed by a hopper, with a capacity of 35 kg of pellets (approx.) and an intermittent top-feed system, where the pellets are conveyed from the hopper to the combustion chamber by a screw that determines the thermal input. An electrical resistance ensures the ignition of the pellets, that are burnt in a combustion chamber containing a small basket with orifices that allow for air influx; an ash pan is used to store the ashes, a fan to remove the fuel gases from inside the combustion chamber and a ventilator that, when turned on, promotes the circulation of external air and warms up the room - during the experimental tests this ventilator was turned off. Figure 1 shows a scheme and a photo of the experimental set-up.

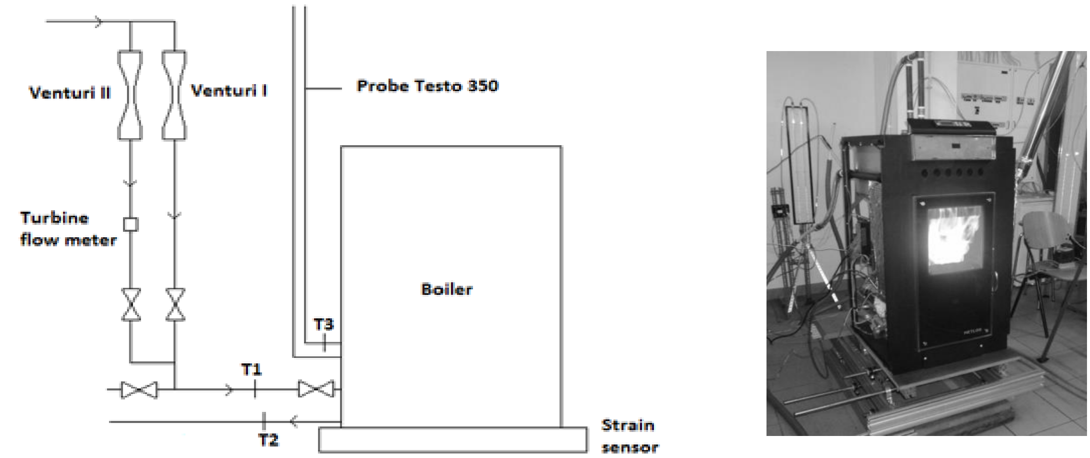

Figure 1: Experimental set-up (scheme and photo) Performance measurements

The inlet and outlet water temperatures were measured by K type thermocouples, T1 and T2 respectively (in the scheme), as well as the stack temperature, thermocouple T3. The thermocouples were connected to a Picolog Recorder through a TC-08 datalogger (uncertainty of 3.93 %). The water mass flow rate was measured using both a Venturi and a turbine flow meter (uncertainty of 2.24 %) that were connected to National Instrument LabVIEW 8.6 software through a NI USB-6008 DAQ datalogger. The pellets mass flow rate was measured by two different methods: one using a strain sensor that weighed the whole boiler setup during the combustion process, connected to Catman datalogger through Sipder 8-30 software; the other was simply weighing the initial and the final mass of pellets in the hopper (uncertainty of 0.0051 %). A Testo 350 Emission Analyzer was used to measure the exhaust gas composition: O_2 (uncertainty of 0.2 %), CO (uncertainty of 0.028 %), CO_2 (uncertainty of 0.388 %) and NO (uncertainty of 0.0005 %), using the software Easy Emission. The efficiency of the boiler was determined using the direct method, Eq(3):

$$\eta = \frac{\dot{Q}_{outup}}{\dot{Q}_{input}} = \frac{\dot{m}_{H_2O} \times c_{H_2O} \times (T_2 - T_1)}{\dot{m}_{pellets} \times LHV_{pellets}} \tag{3}$$

where $\dot{m}_{H_2O}$ is the water mass flow rate (kg/s), c_{H_2O} is liquid water specific heat (kJ/(kg.K)), T_2 and T_1 are the outlet and inlet water temperatures (°C), $\dot{m}_{pellets}$ is the pellets mass flow rate (kg/s) and $LHV_{pellets}$ represents the pellets lower heating value (kJ/kg). The average mass flow rate of the burned pellets is the mass of a consumed batch of pellets contained in the feeding hopper divided by the required time interval.

3. Results and discussion

Several tests were made for Pine and *Acacia dealbata* pellets for reduced, medium and high loads. Reported values represent the average of, at least, four tests for Pine and three for *Acacia.* Initially, due to

the differences in physical characteristics between the two pellet types, for the same standard load, the feed rate was significantly lower with *Acacia* pellets. Later on, to ensure approximately the same mass flow rate of pellets, a built in variable frequency drive was used.
The influence of fuel mass flow rate in the boiler thermal efficiency was studied for the three standard loads (reduced, medium and high) with both pellets and the results are shown in Table 2 and Figure 2.

Table 2: Thermal efficiency (%) for different loads

	Pine	*Acacia dealbata*
Reduced load	46.4	48.7
Medium load	57.7	53.8
High load	64.6	62.0

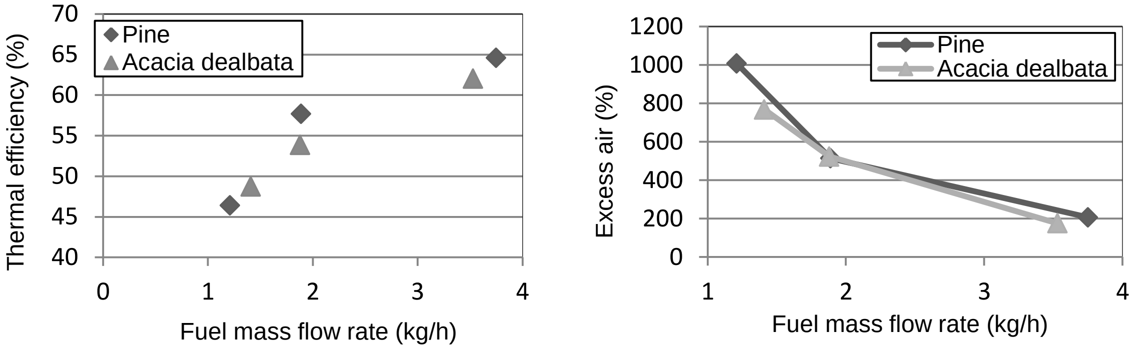

Figure 2: Thermal efficiency and excess air as a function of fuel mass flow rate

For both pellets an increase in the fuel mass flow rate leads, on average, to an increase in the boiler thermal efficiency. The highest efficiency was obtained for high load burning Pine pellets. At reduced load the boiler thermal efficiency was slightly higher for *Acacia* pellets due to a somewhat higher average mass flow rate. For medium and high load there were few differences between using Pine or *Acacia* pellets on the boiler thermal efficiency: on average, 7 and 4 % lower with *Acacia* pellets.
The European standard EN 14785 (2006) establishes a limit for the thermal efficiency at reduced and high loads, which is 70 and 75 %, respectively. As previously observed, both pellets do not comply with these limits, which mean that the boiler design has some flaws. Only under very strict controlled combustion of pine pellets can the boiler operate at minimum acceptable conditions, according to the above mentioned standard.
As can be perceived in Figure 2, excess air decreases with the increase of fuel mass flow rate. Mainly at reduced load, the excess air used in the combustion was extremely high for both pellets. The boiler does not make an automatic adjustment of the air mass flow rate as a function of the fuel mass flow rate being burnt. Therefore, an increase in the fuel mass flow rate leads to a decrease in oxygen concentration in the exhaust gases, once that for approximately the same amount of air, an increase in fuel mass flow rate requires a greater consumption of oxygen in the combustion chamber.
Regarding to emissions, Figure 3 shows the CO and NO_x emissions for Pine and *Acacia* pellets at reduced, medium and high loads. These emissions were corrected to 13 % (v/v) of oxygen in the combustion gases.
CO formation during the combustion process is due to several factors, such as: insufficient excess air, residence time in the combustion chamber limited, poor mixing of fuel and oxidant and low combustion temperature (Roy et al., 2013). The high emissions of this pollutant can be related to one of these factors or a combination of them.
As can be observed for both pellets, CO emissions decrease with the increase in the fuel mass flow rate, diminishing the excess air ratio, thus reducing the CO combustion quenching phenomena and enhancing its burning to CO_2. At reduced, medium and high loads, *Acacia* pellets emitted, on average, 58, 241, and 106 % more CO compared with Pine pellets, respectively. The European standard also establishes a limit for CO emissions: 600 ppm (at 13 % O_2) at reduced load and 400 ppm (at 13 % O_2) at high load. At reduced load the CO emissions were extremely high for both pellets, which do not comply with the standard and, at high load, only Pine pellets comply with it. The highest CO emission when burning *Acacia* compared to Pine pellets, may be related to the fact that the combustion chamber of the boiler was designed to burn pine pellets and there is a need to adjust its geometry and volume for other fuels. Some

other boiler combustion conditions, including the excess air, must also be adjusted to the specific type of fuel and its mass flow. One other situation is the fuel feed system. Since it operates on an intermittent basis it causes some instability in the combustion and therefore some CO fluctuations.

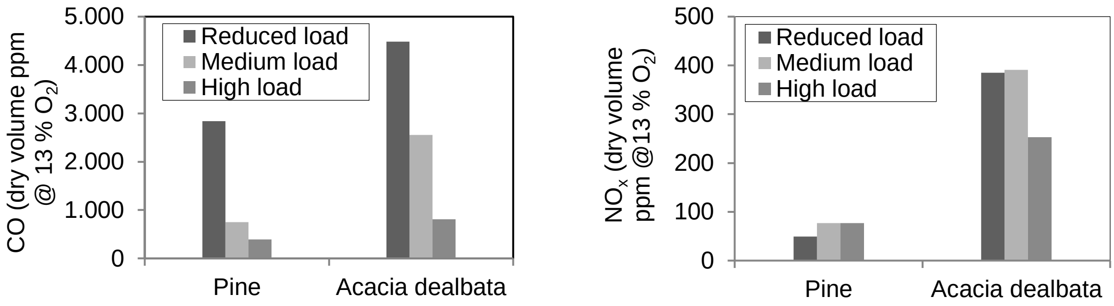

Figure 3: CO and NO_x emissions for Pine and Acacia *pellets at reduced, medium and high loads*

With respect to the NO_x emissions, the pellet type had a significant effect (Khan et al., 2009). The nitrogen oxides include NO, NO_2 and N_2O, being the first main source of nitrogen oxides. NO formation during the combustion is mainly due to three mechanisms: 'thermal NO' - with high temperatures, dissociation of the atmospheric nitrogen and oxygen takes place; 'fuel NO' - due to the elemental nitrogen content of the fuel; and 'prompt NO' - due to the fast reaction at the flame front (Liu et al., 2013) and frequent in regions of rich air fuel mixtures. In face of high excess air values and moderate combustion temperatures registered, well below typical small domestic boilers' 1,300°C (Verma et al., 2012), and the amount of nitrogen in the tested fuels, the 'fuel NO' mechanism is the major cause for NO formation (Rabaçal et al., 2013). Thus, the significant difference in NO_x emissions for both pellets is a consequence of the inherent nitrogen content of the species (Mahmoudi et al., 2010).

4. Conclusions

The performance assessment of *Acacia dealbata*, an invasive species, as fuel for domestic pellet boilers was analysed. The thermal efficiency and the emissions burning Pine and *Acacia* pellets have been tested.
The obtained results show that an increase in the fuel mass flow rate leads to an increase in the boiler thermal efficiency. The best boiler thermal efficiency was achieved with Pine pellets. On average, the boiler thermal efficiency was 7 and 4 % lower with *Acacia* pellets at medium and high loads, respectively, compared with Pine pellets. Nevertheless, regardless of load or type of pellets, the boiler thermal efficiency does not comply with EN14785 standard and it was, on average, 31 and 16 % lower than the minimum limit established by that standard, for reduced and high loads, respectively.
The fuel mass flow rate has a significant effect in oxygen concentration in the exhaust gases. Exhaust gas analysis revealed that the boiler´s manufacturer programmed excess air was excessive for each of the predefined operational loads, leading to poorer efficiency performances.
Concerning emissions, the fuel mass flow rate and the type of pellet had a significant effect. The CO emissions decrease with the increase in the fuel mass flow rate and, for the three loads, were always higher with *Acacia* pellets. At reduced load, the worst case, CO emissions were five and seven times higher than the maximum limit, respectively for Pine and *Acacia*, established by the above referred standard (EN 14785, 2006). With respect to NO_x emissions, a significant effect of the pellet type was observed. On average, burning *Acacia* released five times more NO_x than when Pine pellets were used.
Overall, the type of pellets had a significant effect on the boiler performance. *Acacia* revealed a worse performance when compared to Pine.

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