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PERFORMANCE ASSESSMENT OF A DOMESTIC BOILER USING PELLETS MADE FROM *CYTISUS MULTIFLORUS* INVASIVE SHRUBS COMPARED WITH COMMERCIAL PINE

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Abstract. *A commercial model of a 20kW nominal thermal output wood pellet boiler was tested at three operational standard loads: reduced, medium and high. The influence of pellet type, mass flow rate and excess air in the global performance of the boiler were studied. The fuel used was pelletized* Cytisus spp.*, an invasive shrub species. Thermal data was compared to values obtained burning commercial pine pellets. The combustion efficiency was determined using the direct method. A Testo 350 analyser measured stack temperature and composition (O_2, CO, CO_2 and NO). The water mass flow rate was measured using both Venturi and turbine devices. A strain sensor weighed the whole boiler thus continuously measuring pellets mass flow, through the knowledge of the pellet batch consumption rate. When establishing the same standard load for both of pellets, the feed rate was lower with shrub pellets, which resulted in lower thermal input when compared to pine pellets. Alternatively, a built in variable frequency drive was used to ensure the same mass flow rate of pellets. CO and NO emissions were higher at reduced load and, on average, higher with Cytisus than with Pine. Excess air was adjusted to different mass flow rates of pellets and fixed furnace geometry, increasing the global boiler efficiency above primary base reference experiments. Nonetheless, the higher efficiency that was achieved with standard higher operating load, failed to comply with EN 14961-2.*

Keywords: *pellet boiler, invasive shrubs, emissions, efficiency*

1.INTRODUCTION

Portugal, as well as Europe and the remaining world, is passing through an energy crisis. In 2009, 80% of primary energy consumed in Portugal came from fossil fuels (IEA, 2009). Portugal, alike many other countries, has no fossil fuel reserves that ensure energetic needs. According to the International Energy Agency, in 2009 oil represented 50% the total consumption of primary energy in Portugal, natural gas 18% and coal 12%. 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).

The use of biomass as a fuel has several environmental, social and economic advantages that can be exploited and may contribute to sustainable development (Khan *et al.*, 2009). 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; Demirbas, 2004).

The combustion of biomass for heating purposes is one of the oldest processes of energy conversion known to mankind. It is more difficult than the combustion of fossil fuels, because the biomass has a more complex physical and chemical composition (Tabarés *et al*., 2000).

The main properties of biomass that should be considered when it is used as an energy source are: moisture content, calorific value, fixed carbon, volatiles, ash and cellulose/lignin ratio (McKendry, 2002). In a 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 and storage is complicated (Kaliyan and Morey, 2009; 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).

The main purpose of this work is to evaluate the performance of a commercial pellet boiler using *Cytisus multiflorus*, an invasive species. The obtained results were compared with those obtained with previously tested commercial Pine pellets. The adequacy of using an invasive species as a raw material to produce pellets was evaluated.

The thermal efficiency and emissions of the above mentioned pellets were compared at three different operation loads: reduced, medium and high. A correction in the excess air adjustment was carried out to improve the boiler performance.

2. MATERIALS AND EXPERIMENTS

2.1. Sample preparation

For the present work, two different types of pellets were used: *Pinus pinaster* and *Cytisus multiflorus*. Pine pellets were acquired to a Portuguese company and they are currently commercialized in Portugal. *Cytisus multiflorus* pellets were manufactured specifically for this work. For this, *Cytisus multiflorus* was collected in a forest in the region of Viseu and dried in a solar kiln, with the moisture content monitored. The drying process was carried out in the summer and took four days with a 9.75% daily drying rate. Afterwards, a GKLC-19PK2010 hammer mill grounded the raw material and its product output passed through a 4 mm screen. The mean diameter of the samples was 459 ± 58 μm, after being screened in an AS200 Retsch shaker. Each sieving was made for 10 minutes with 1.50 mm amplitude. Pellets of *Cytisus multiflorus* with 6 mm diameter were produced in an AGP GK5500 pelletizer press with a mass feed rate of 100 kg/h. Figure 1 and 2 show the pellets manufactured and used in the experiments.

Figure 1. *Pinus pinaster* pellets.

Figure 2. *Cytisus multiflorus* pellets.

2.2. Pellets characterization of *Pinus pinaster* and *Cytisus multiflorus*

2.2.1 Physical characterization

In order to evaluate the characteristics of experimental pellets 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 0.1 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 FprEN 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 and dry basis, was determined according to Eq.s (1) and (2), respectively:

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

$$\mathrm{MC_{db}}\,(\%) = \frac{m_w - m_d}{m_d} \times 100 \tag{2}$$

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

Tests of mechanical durability were made for three samples of each type of pellets, using a tumbling device defined by ASAE S 269.4. Thereby, a 500 g sample was manually sieved with a 3.35 mm round hole sieve and then tumbled for 500 rotations during 10 minutes (Temmernan *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. (3):

$$\text{Durability}\,(\%) = \frac{Mass\ of\ pellets\ after\ trumbling}{Mass\ of\ pellets\ before\ trumbling} \times 100 \tag{3}$$

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

Table 1. Characteristics of the experimental pellets.

	Pinus pinaster	*Cytisus multiflorus*
Diameter (mm)	6.15 ± 0.06	6.22 ± 0.09
Length (mm)	20.9 ± 0.18	22.2 ± 4.61
Mass (g)	0.755 ± 0.02	0.64 ± 0.16
Particle density (kg/m^3)	1190.8 ± 18.98	951.8 ± 182.4
Moisture content (% wb)	5.9 ± 0.208	7.1 ± 0.295
Mechanical durability (%)	99.2 ± 0.058	95.9 ± 0.755

The obtained results show few differences between the physical properties of pellets made of Pine and of *Cytisus multiflorus*. Mass and particle density were those presenting the highest differences.

Relatively to moisture content, *Cytisus multiflorus* pellets had higher moisture content (see Tab.1), below the established 10% by with EN 14961-2, nonetheless. The mechanical durability achieved with *Cytisus* pellets was below the minimum established for the same standard, which is 97.5%. During the transport of pellets from the hopper to the combustion chamber, to achieve a constant fuel mass flow, the physical properties of pellets have a great importance (Verma *et al.*, 2011).

2.2.2 Chemical characterization

The ultimate and proximate analysis of *Cytisus multiflorus* were made by LNEG- National Laboratory of Engineering and Geology in Lisbon, Portugal. The LHV was determined under DIN EN 14918. The proximate analysis shows higher volatiles content in the case of *Cytisus multiflorus*, as wells as a greater ash content, compared to Pine. Regarding to the ultimate analysis, a similar composition between both pellets can be seen, with the exception of the nitrogen content (that is 2.2 times higher for *Cytisus* pellets compared with Pine pellets). The sulfur content is low for both pellets, Tab. 2.

Table 2. Chemical composition of *Pinus pinaster* and *Cytisus multiflorus*.

	unit	*Pinus pinaster*(1)	*Cytisus multiflorus*
Ash	(%, m/m)	0.82	1.4
Volatile	(%, m/m)	76.28	81.6
Fixed C	(%, m/m)	22.89	17.0
Total C	(%, m/m)	51.12	50.2
Total H	(%, m/m)	6.07	6.0
N	(%, m/m)	0.49	1.1
S	(%, m/m)	0.01	<0.06
LHV	(kJ/kg)	17500	18491

(1)Serrano *et al.*, 2011

2.3. EXPERIMENTAL SETUP

The boiler used in the tests was an Aqualux, from METLOR, a commercial 20 kW nominal thermal output, made in Portugal.

The boiler is composed by a hopper with a capacity of 35 kg of pellets (approx.), 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 pellets, that are burnt in a combustion chamber containing a small basket with orifices that allow air admission; 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 3 shows a scheme and a photo of the experimental set-up.

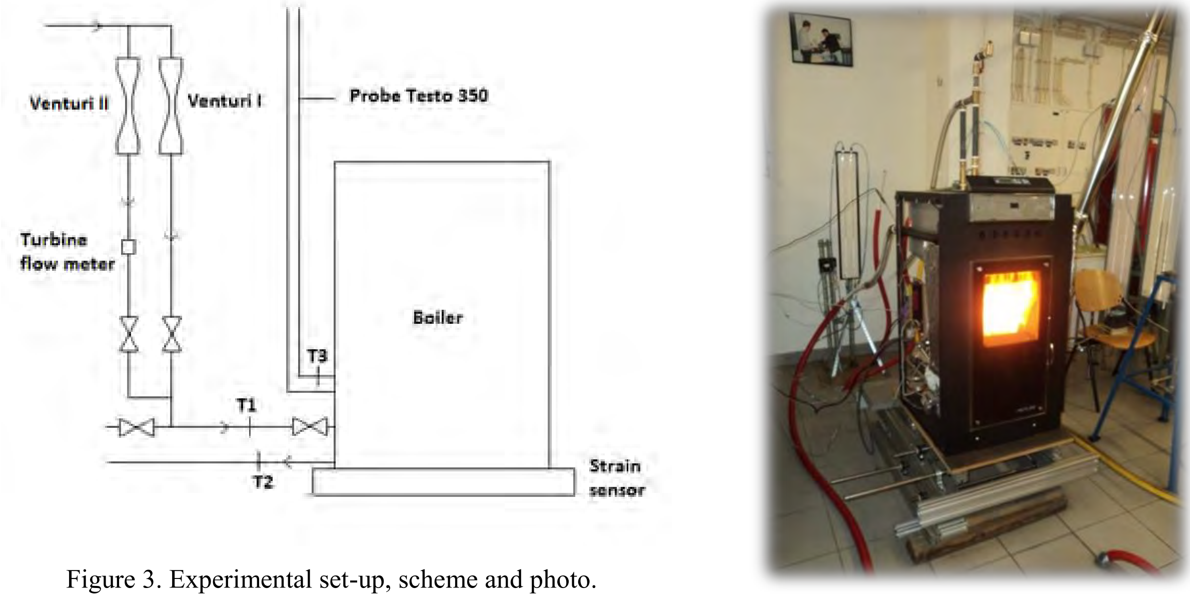

Figure 3. Experimental set-up, scheme and photo.

2.3.1 Performance measurements

The inlet and outlet water temperatures were measured by type K 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. The water mass flow rate was measured using both a Venturi and a turbine flow meter 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. A Testo 350 Emission Analyser was used to measure the exhaust gas composition: oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NO), using the software Easy Emission.

The efficiency of the boiler was determined using the direct method, Eq. (4):

$$\eta = \frac{\dot{Q}_{outup}}{\dot{Q}_{input}} = \frac{\dot{m}_{H_2O} \times c_{H_2O} \times (T_{outlet} - T_{inlet})}{\dot{m}_{pellets} \times LHV_{pellets}} \tag{4}$$

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_{out} and T_{in} represents the outlet and inlet water temperatures (°C), $\dot{m}_{peletes}$ 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 ratio of the mass of a consumed batch of pellets contained in the feeding hopper by the required time interval.

3. RESULTS AND DISCUSSION

Several tests were made for both pellets (Pine and *Cytisus multiflorus*) for reduced, medium and high operating loads. Reported values represent the average of, at least, four tests for Pine and two for *Cytisus*.

3.1. Influence of fuel mass flow rate

The influence of fuel mass flow rate in the boiler thermal efficiency was studied for the three standard loads, predefined by the manufacturer. Initially, due to the differences in physical characteristics between Pine and *Cytisus multiflorus* pellets, for the same standard load, the feed rate was significantly lower with *Cytisus* pellets. Later on, to ensure approximately the same mass flow rate of pellets, a built in variable frequency drive was used.

The influence of the fuel mass flow rate on the boiler thermal efficiency can be observed in Fig. 4. An increase of the fuel mass flow rate leads, on average, to an increase in the boiler thermal efficiency. The highest efficiency was obtained for high load and the lowest was achieved for reduced load (below 50%). Figure 4 thermal efficiency data has assigned excess air values of 1008, 514 and 207%, respectively for fuel mass flow rates of 1.21, 1.89 and 3.75 kg/h, for Pine, and, 942, 563 and 189%, for fuel mass flow rates of 1.31, 1.85 and 3.33 kg/s, for *Cytisus* pellets.

On average, the boiler thermal efficiency was approximately 10% higher with Pine pellets compared with *Cytisus* pellets.

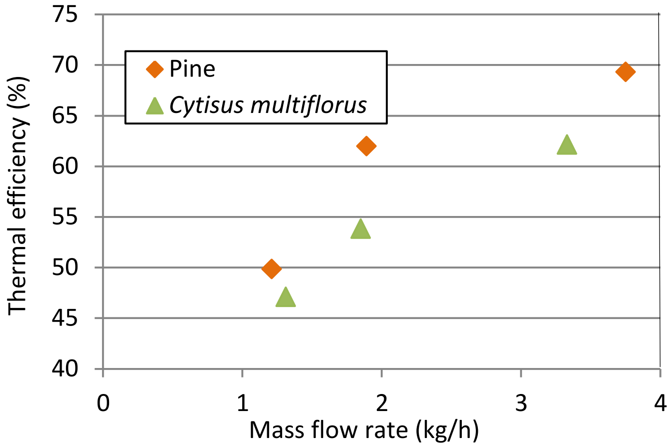

Figure 4. Thermal efficiency *versus* fuel mass flow rate.

Figure 5 shows the CO and NO_x emissions for Pine and *Cytisus* pellets at reduced, medium and high load, during the stationary period. These emissions were corrected to 13% (v/v) of oxygen in the combustion gases.

As can be seen for both type of pellets, CO emissions decrease with the increase in the fuel mass flow rate. At reduced, medium and high loads, *Cytisus* pellets emitted, on average, 77, 228, and 38% more CO compared with Pine pellets, respectively.

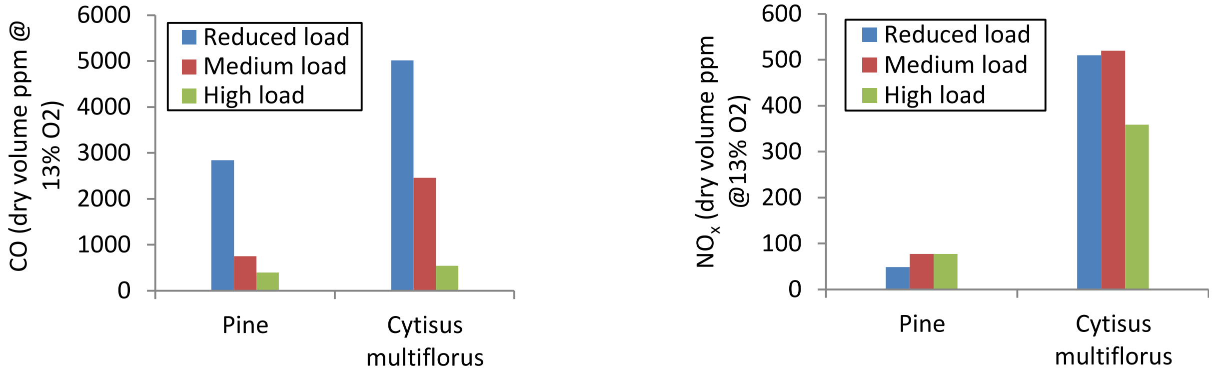

Figure 5. CO and NOx emissions for Pine and *Cytisus multiflorus* pellets at reduced, medium and high load.

The CO emissions at reduced load were extremely high for both pellets, which do not comply with EN14785 as this standard establishes 600 ppm (at 13% O_2) as a limit for CO emissions at reduced load. For high load the limits have been complied only by Pine pellets.

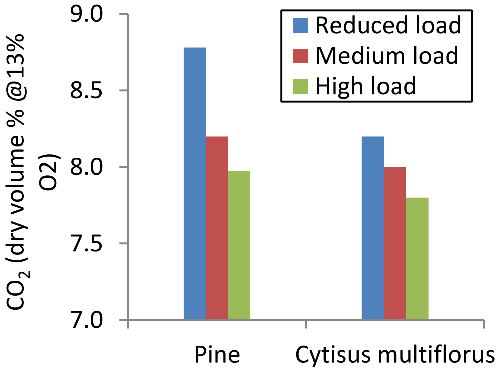

Figure 6. CO_2 emissions for Pine and *Cytisus multiflorus* pellets at reduced, medium and high load.

With respect to the NO_x emissions, the fuel mass flow rate had no significant effect. With Pine the NO_x emissions were very similar for the three loads. With *Cytisus multiflorus* the NO_x emissions were similar at reduced and medium load, and 44% lower with high load. Once again the NO_x emissions were higher for *Cytisus* pellets when compared to Pine.

NO_x formation during the combustion is mainly due to three mechanisms: 1^{st}- thermal NO_x - with high temperatures, dissociation of the atmospheric nitrogen and oxygen takes place; 2^{nd}- fuel-NO_x – due to the elemental nitrogen content of the fuel and 3^{rd}- prompt NO_x - due to the fast reaction at the flame front (Khan *et al.*, 2009; Verma *et al.*, 2011) and frequent in regions of rich air fuel mixtures. This last case does not apply in the present situation. On the other hand, for the case of small domestic boilers where combustion temperatures are below 1300°C, the fuel-NO_x mechanism is the major cause (Verma *et al.*, 2011a). The significant differences (Tab. 2) in NO_x emissions is the consequence of the nitrogen content in the pellets (Tab.2), which is 2.2 times higher for *Cytisus* compared to Pine. Regarding CO_2 emissions, these were somewhat higher with Pine pellets; and are not influenced by fuel mass flow rate. The higher CO and consequently lower CO_2 emissions for *Cytisus* pellets is a clear indication of lower combustion quality achieved with these pellets.

Figure 7 shows the measured oxygen concentration and the excess air, in the flue gases, as a function of the fuel mass flow rate, for Pine (left) and *Cytisus* (right) pellets. As can be observed, the oxygen concentration decreases with the increase in the fuel mass flow rate. For approximately the same amount of air, an increase in fuel mass flow rate requires a greater consumption of oxygen in the combustion chamber, leading to a decrease in its concentration in the flue gases (González *et al.*, 2004a). With respect to the excess air coefficient, an increase in flue mass flow rate leading to a decrease in excess air was verified. This fact is explained due to a larger consumption of oxygen in the combustion.

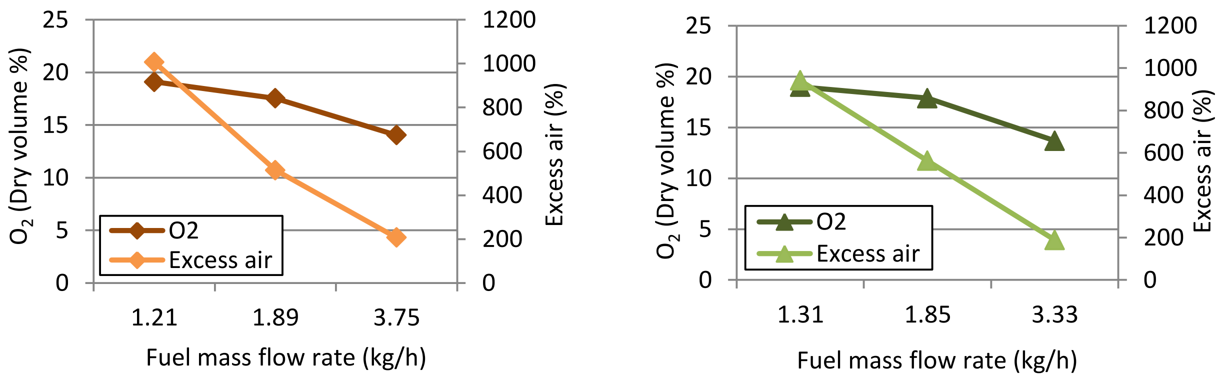

Figure 7. O_2 and excess air coefficient *versus* fuel mass flow rate for Pine (left) and *Cytisus multiflorus* (right) pellets.

Table 3 shows the boiler experimental conditions and some combustion parameters for burning Pine and *Cytisus* pellets. The obtained results show that an increase in the fuel mass flow rate leads to an increase in exhaust gases temperature. This temperature was very similar with both types of pellets. The fuel mass flow rate also affects the heat losses in the exhaust gas, being these higher at higher fuel mass flow rate.

Table 3. Boiler experimental conditions and combustion parameters.

	Fuel mass flow rate (kg/h)	Thermal input (kW)	Exhaust gases temperature (°C)	Exhaust gas heat losses (kW)
Pinus p.	1.21	5.86	109.35	1.97
	1.89	9.18	158.60	2.56
	3.75	18.24	247.78	4.30
Cytisus m.	1.31	6.71	111.65	2.19
	1.85	9.48	147.52	2.70
	3.33	17.11	231.82	3.40

3.2. Influence of excess air

For the three loads the excess air flow, predefined by the manufacturer, was proven to be excessive. Therefore, the excess air was adjusted for the three different loads. The following figures show the average of the results in different tests achieved when air excess was decreased.

Figure 8 shows the thermal efficiency according to fuel mass flow rate. It can be observed that the highest efficiency was now obtained with medium load. For Pine pellets, now burned with a reduced air excess, the boiler efficiency had an increase of 31, 22 and 8%, respectively for reduced, medium and high load, and, for *Cytisus,* an increase of 38, 26 and 5%, for the same loads, respectively. The highest increase in efficiency was achieved with reduced and medium loads. Due to this increase, the limits of boiler thermal efficiency at high load, burning Pine pellets, was in compliance with EN14785 (75%). However, at reduced load the thermal efficiency was still not fulfilling the requirements.

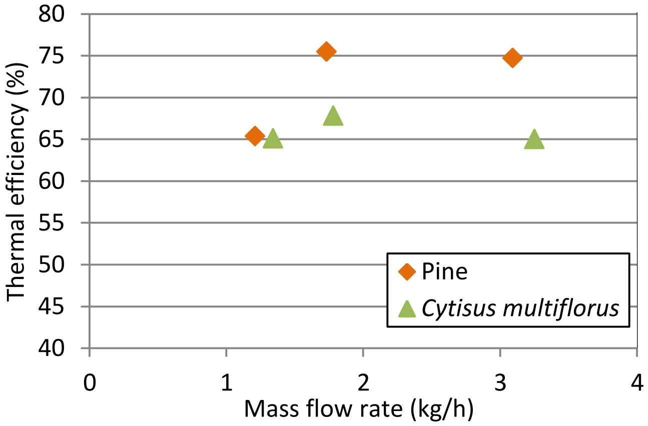

Figure 8. Thermal efficiency *versus* fuel mass flow rate.

Figure 9 shows the measured oxygen concentration in the fuel gases and the excess air as a function of the fuel mass flow rate. Comparing the results of these tests with the previous ones, a decrease in the excess air was verified, as well as a lower oxygen concentration in the exhaust gases, as expected. At reduced load with Pine pellets, the excess air was 59% lower than in first tests (Fig. 7), which led to a 31%, increase in the boiler thermal efficiency, for the same mass flow rate. As for oxygen concentration, there was an 11% decrease when compared to the first tests. The same results were achieved when *Cytisus* pellets were tested.

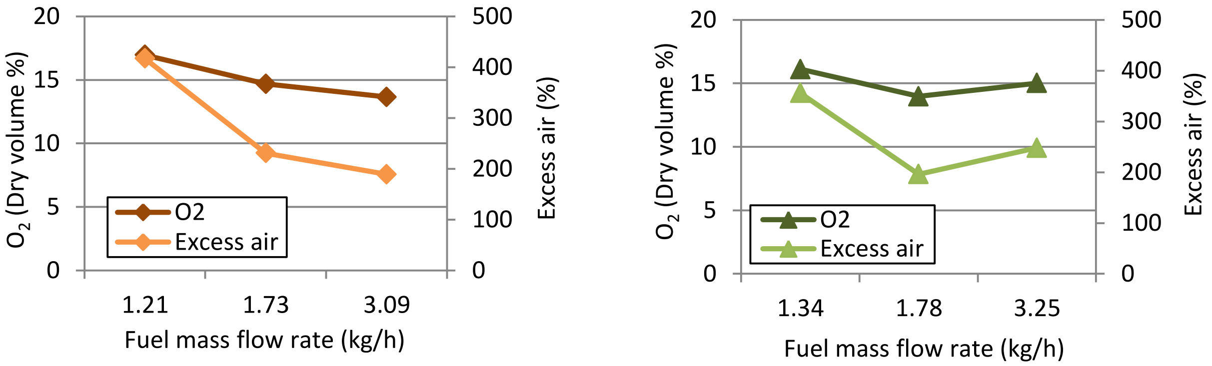

Figure 9. O_2 and excess air coefficient *versus* fuel mass flow rate for Pine (left) and *Cytisus multiflorus* (right) pellets.

Table 4 shows the boiler experimental conditions and some combustion parameters for the tests with lower excess air. The obtained fuel mass flow rate in these tests was quite similar to the first tests; thereby a comparison between the two sets of experiments will be presented.

Table 4. Boiler experimental conditions and combustion parameters.

	Fuel mass flow rate (kg/h)	CO (dry vol. ppm)	NO_x (dry vol. ppm)	CO_2 (dry vol. %)	Exhaust gas temperature (°C)	Exhaust gas heat losses (kW)
Pinus p.	1.21	598	56	8.06	95.12	0.98
	1.73	361	66	7.96	120.98	0.95
	3.09	410	71	7.93	248.62	3.3
Cytisus m.	1.34	890	256	7.80	115.0	0.9
	1.78	636	262	7.86	137.65	1.1
	3.25	926	324	7.89	262.98	4.6

As expected, the excess air decrease has a significant affect in the emissions, leading to a huge decrease in CO emissions with both pellets. The reduced operating load has led to the greater decrease in CO emissions. Comparing with the initial tests, a decrease of 79 and 52% in CO emissions was verified for pine pellets, respectively for reduced and medium load; for *Cytisus,* a decrease of 82 and 74%, for the same loads, respectively. Regarding high load and for the two types of pellets, a decrease in CO emissions has not been reached as the fuel mass flow rate achieved with these tests was lower and therefore a decrease of the excess air was necessary in order to improve the boiler performance. With respect to CO_2 emissions, a slight decrease was verified.

On average, there was a decrease in exhaust gases temperatures when comparing to the first tests. With the exception of the high load with *Cytisus* pellets, the exhaust gas heat losses had a significant decrease, mainly due to the temperature and CO emissions decrease. This means that a decrease in excess air leads to a decrease in these losses and that such correction would be virtuous for the manufacturer product quality.

4. CONCLUSIONS

The thermal efficiency and the emissions of a domestic pellet boiler burning Pine and *Cytisus* pellets have been tested. The boiler was tested at three different operation loads for both pellets. The influence of pellet type, mass flow rate and excess air in the boiler performance were analyzed.

An increase in fuel mass flow rate leads to an increase in the boiler thermal efficiency. The best efficiency was obtained when burning Pine pellets at high load; the lowest was achieved for reduced load burning *Cytisus* pellets. On average, the boiler thermal efficiency was approximately 10% higher with Pine pellets compared with *Cytisus* pellets. Regardless of load or type of pellets, the thermal efficiency does not comply with EN14785 standard.

Concerning emissions, the fuel mass flow rate and the pellets type had a significant effect on CO emissions. They decrease with the increase in the fuel mass flow rate and, for the three loads, CO emissions were always higher with *Cytisus* pellets. At reduced load, for both pellets, CO emissions were extremely high and, once again, do not comply with EN14785. With respect to NO_x emissions, a important effect of the fuel mass flow rate was not verified; nonetheless, the pellet type has a significant effect. The higher emissions observed with *Cytisus* pellets is the result of higher elemental nitrogen content in this species compared to Pine. As expected, an increase in the fuel mass flow rate leads to a decrease in the oxygen concentration (and excess air). The exhaust gas heat losses were higher at higher fuel mass flow rate and, on average, higher with *Cytisus* pellets.

The decrease in the excess air has proven to increase the boiler performance: for both pellets the thermal efficiency had a significant increase when the excess air was reduced. Even so, only burning Pine pellets at high load did comply partially with EN14785 standard, *i.e.*, it complies for thermal efficiency but not for emissions level; at reduced load, the thermal efficiency does not comply. *Cytisus* pellets do not fulfil, therefore, with EN14785 requirements at any load.

For these corrected conditions, stack monitoring revealed a decrease in the excess air/oxygen concentration. The CO emissions were minimized using a lower excess air, compared to the manufacturer's defaults. Comparing with the first tests made, before the excess air adjustment had been done, this decrease was fairly high at reduced and medium load. Regarding NO_x, there was an emission reduction.

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