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EXCESS AIR INFLUENCE ON THE THERMAL EFFICIENCY OF DOMESTIC BOILERS BURNING PINE PELLETS

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Abstract. *This work studied how the standard settings defining excess air used in common domestic boilers burning Pine pellets influence the thermal efficiency. Commercial and ENplus certified Pine pellets were burned in a boiler varying the amount of air supplied to the combustion process in three nominal thermal loads: reduced, medium and high. Initial essays were performed using the manufacturer's indicated parameter of air regulation for each load. As previous works had shown that the excess air value was way too high, thus affecting negatively the combustion process, experiments were carried out were the amount of air was progressively reduced to obtain a point of maximum efficiency. Simultaneously, the pollutant emissions of* O_2*, CO,* CO_2 *and* NO_x *were measured to allow determining the excess air value for each essay. Boiler thermal efficiency increases by lowering the excess air, e.g., thermal efficiency of the medium load increased from 58 to 74% with excess air values decreasing from 565 to 193%, respectively. CO emissions reductions accompanied this excess air decrease. To define the excess air value that would point out maximum thermal efficiency, experiments were carried out so that gases dew-point temperature was attained. In so doing, slightly higher values of thermal efficiency were obtained but at the expense of extremely high pollutant emissions.*
Keywords: *excess air, thermal efficiency, combustion, pellets, Pine*

1. INTRODUCTION

Biomass is identified as economically viable energy source just for a few decades but in reality, it is a renewable energy source that has been used for thousands of years. After oil, coal and natural gas, is the source most used (REN 21, 2013). By 2013 in Portugal, 50% from all of the renewable energy had provenance in biomass, influencing primary and final energy consumption in 11 and 14%, respectively (DGEG, 2015). It is considered a form of green energy available and its neutral character in Carbon dioxide balance, as it has already been absorbed in the growth period, turns biomass into an important agent as alternative to fossil fuels. Although fossils presents some stronger characteristics than biomass like the higher heat value, availability and abundance, its effect on greenhouse gas, and the consequent armful climatic changes, and the dependence that importers countries have on fossil exporter's, makes it critical its gradual replacement for green energy sources. In biomass combustion the parameters that have more influence are: moisture content, calorific value, fixed carbon, volatiles, ash and cellulose/lignin ratio (McKendry, 2002).

Pellets certification in Europe is guided by ENplus (EPC, 2013), sustained on EN ISO 17225-2: 2014 standard. In 2014 the number of companies certified by ENplus was 203 in 31 countries (AEBIOM, 2015a), 8 of which in Portugal (ANPEB, 2015); production by certified producers amounted to a total of 6.7 million tons in the European Union (AEBIOM, 2015a). Portugal was, in 2013, the second exporter of pellets in Europe, surpassed only by Latvia, sending a total of 776,736 tons, particularly to UK, Denmark and the Netherlands (AEBIOM, 2015b). At the end of 2013 there were 26 pellets production plants, most concentrated in the northern coastal and center, where were produced about 900,000 tons of pellets (ANPEB, 2015). Pine was the raw material most used in pellets production, representing about 80% in 2012; other species used for this purpose were Eucalyptus, Poplar, Acacia and Oak.

In ENplus standard, three classes of pellets are distinguished according to the characteristics of the raw material and final product quality requirements: ENplus-A1: pellets that meet the most demanding quality requirements, with ash low production and for use in boilers and other household burning equipment; ENplus-A2: pellets which are used in larger installations and generate greater amount of ash; EN-B: intended for industrial use. Pine pellets utilized in this work are Enplus-A1certified.

In a previous study using the same boiler and in a similar experimental setup (Ferreira, 2013) it was concluded that excess air values predefined by the boiler manufacturer in each selectable thermal load, which corresponds to different fuel mass flow rates, are above the desirable, in order to achieve greater thermal efficiency with lesser pollutants emissions.

The main purpose of this work was to analyse the influence of lowering excess air in the combustion of ENplus certified Pine pellets, so that a maximum boiler's thermal efficiency was attained, accompanied with minimum pollutants emission. 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.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

Pine pellets were obtained from Pinewells, a Portuguese company (Fig. 1).

Figure 1. Pine pellets.

Since the sample brand, methods and instruments are the same in this work as are in Ferreira's (2013), the values were obtained from that study. Physical characterization was performed as described below.

According to ÖNORM M7135, the length and diameter of twenty pellets for each of three samples were measured with a digital caliper with 0.1 mm precision. The correspondent mass was determined using the Precisa 6200 precision scale. It was obtained a pellet length of 20.9 mm and diameter of 6.1 mm. Trough the relation between pellet mass and volume, considering the sample a cylinder (*Rabier et al*., 2006), allowed to determine a particle density of 1190.8 kg/m^3.

Pellets moisture content was established according to EN 14774-2:2009. Later on, resorting to a Venticell 50 L oven at a temperature of 105±2ºC pellet samples were dried, until constant mass was observed. Moisture content in wet basis was determined by Eq. (1).

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

where m_w is the initial wet mass and m_d the dry mass. MC_{wb} was 5.9%.

To determine mechanical durability, three samples were placed 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 afterwards tumbled 500 rotations in 10 minutes (Temmerman *et al*., 2006). The remaining pellets were weighed after sieving the sample again. Mechanical durability was determined by Eq. (3).

$$Durability\ (\%) = \frac{m_{p\_final}}{m_{p\_inicial}} \text{x}100 \tag{2}$$

where m_{p_final} represents the pellets mass after tumbling and $m_{p\_inicial}$ the pellets mass before tumbling. The mechanical durability was 99.2%.

Chemical data about Pine was provided by the manufacturer. Table 1 presents physical characterization, proximate and ultimate analyses, in dry basis, and respective limits of the ENplus standard, when existent.

Table 1. Pine physical and chemical properties and ENplus limits.

	Unit	Pine	ENplus-A1
Lenght	mm	20.9	$3.15 \leq L \leq 40$
Diameter	mm	6.1	6 or 8
Particle density	kg/m^3	1190.8	≥ 600
Moisture content (wb)	%	5.9	≤ 10
Mechanical durability	%	99.2	≥ 97.5
Ash	% (m/m)	0.68	≤ 0.7
Volatile	% (m/m)	-	-
Fixed Carbon	% (m/m)	-	-
Total Carbon	% (m/m)	50.6	-
Hydrogen	% (m/m)	6.4	-
Nitrogen	% (m/m)	<0.005	≤ 0.3
Sulfur	% (m/m)	0.01	≤ 0.03
Chlorine	% (m/m)	<0.005	≤ 0.02
Oxygen	% (m/m)	42.9	-
LHV	MJ/kg	18.79	$16.5 \leq PC \leq 19$

2.2 Experimental methodology

The tests were performed in a 20 kW nominal thermal boiler, Aqualux model, from the Portuguese company METLOR. The feeding occurs by top where a 35 kg pellets capacity hopper is connected to an intermittent screw, in which operation/pause time defines the thermal input. An electric resistance in contact with a part of the pellets triggers the ignition, which causes flame propagation throughout the pellets and air mass. The water circulating in the heat exchanger tubes and air ambient become heated by the energy generated during combustion. Every 20 minutes, cleaning mode is activated for 20 seconds, and the ash generated is dragged from the side walls to a removable tray by action of the supplied air in the maximum power. Flue gas is connected to the laboratory exhaustion gases system, which was turned on during the initial minutes of the tests and shut off only when they ended.

The tests were performed by lowering excess air until maximum thermal efficiency is found, but in some of the tests the low air excess decreased the temperature in the combustion chamber to the point where combustion products reached dew point temperature, causing the interruption of the combustion by the boiler safety system. Even though the boiler is a model for domestic use, this one was different, regarding the lack of insulation, except in the flue gas, in order to apply the measurements instruments. The insulation allows reducing losses by convection and radiation which promotes a temperature increase in the combustion chamber and, consequently, the water outlet temperature will rise and thermal efficiency will be higher.

Figure 2. Installation scheme and boiler photo before and after insulation

2.3 Performance calculations

To measure water inlet (*T*1) and outlet (*T*2) and exhaust gases (*T*3) temperatures, K type thermocouples were used; were connected to a TC-08 data logger linked, via USB, to Picolog Recorder. The water mass flow rate was measured by a meter, which was connected to a NI USB-6008 DAQ data logger that transmitted the signal to National Instrument LabVIEW 8.6. Initial and final mass in the hopper was determined by its weighing in a scale, 6200 D model by Precisa. The ratio between the mass difference and the time interval of the test is the pellets mass flow rate. Exhaust gas composition was measured 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).

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

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).

3. RESULTS AND DISCUSSION

The results represent the average of two or three tests, in the different loads, lowering the excess air progressively; are presented in Tab.2.

Table 2. Boiler experiments results for each load.

	Test	Excess air (%)	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)
Reduced	1	1150.00	6.01	1.15	50.06	3485.18	7.16	45.27	115.67
	2	443.40	6.05	1.16	68.29	754.65	7.40	59.95	126.15
	3	293.5	5.68	1.09	74.88	467.69	7.43	55.69	103.71
	14	242.8	5.86	1.12	78.51	288.3	7.49	58.64	105.43
Medium	4	564.87	9.66	1.85	57.89	1248.28	7.22	67.89	177.41
	5	376.9	9.41	1.80	67.26	256.65	7.10	73.31	187.57
	6	193.00	9.64	1.85	73.70	164.00	7.34	62.55	171.76
	7	202.90	9.44	1.81	74.51	1191.62	7.22	48.42	128.07
	15	-	9.28	1.78	77.65	-	-	-	166.00
High	8	240.97	17.68	3.39	64.44	201.71	7.37	78.52	287.01
	9	239.40	17.27	3.31	63.84	281.43	7.35	79.87	282.77
	10	213.50	16.13	3.09	62.78	251.21	7.34	76.80	268.90
	11	207.60	18.88	3.62	66.31	213.98	7.50	77.07	304.90
	12	124.80	18.09	3.47	69.29	110.68	7.34	60.58	284.31
	13	-	17.94	3.44	68.03	-	-	-	284.31
	16	-	16.66	3.19	77.45	-	-	-	290.06

The tests 1, 4 and 8 are the ones performed with manufacturer excess air and fuel mass flow rate parameters and tests 14, 15 and 16 are the one regarding the boiler with insulation and they will be reviewed in a different and, for that matter, referenced chapter.

3.1 Influence of excess air

Figure 3 shows the effect of excess air in boiler's thermal efficiency. Unfortunately, there were no possibilities to measure lower values, to obtain a maximum, since pollutant emissions were too high to be measured by the analyzer.

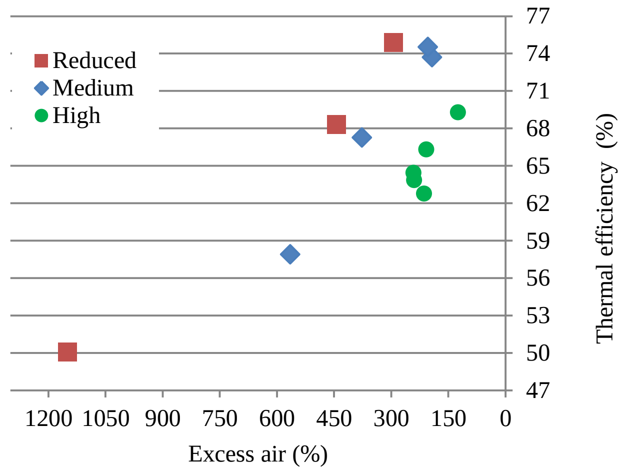

Figure 3. Excess air effect in boiler thermal efficiency.

Still, decreasing the excess air has a very significant influence in boiler's thermal efficiency, with a maximum increase of 24.8, 16.6 and 4.8 percentage points, in reduced, medium and high load, respectively. These expressive differences reveal that excess air predefined by the manufacturer is, in the perspective of improving thermal efficiency, much higher than it would be necessary for the required air quantity in the combustion of the correspondent fuel mass flow rate, especially in reduced and medium load. The slighter difference in high load is due to a great increase in fuel mass flow rate, almost the double, and to a small increase in the air supplied to the combustion.

Concerning EN 14785:2006 standard, which establishes minimum values for reduced (70%) and high load (75%), with pre-defined manufacturer parameters these limits are not respected; even decreasing excess air, only reduced load achieves it.

The effect of excess air in pollutants emissions is shown in Fig. 4.

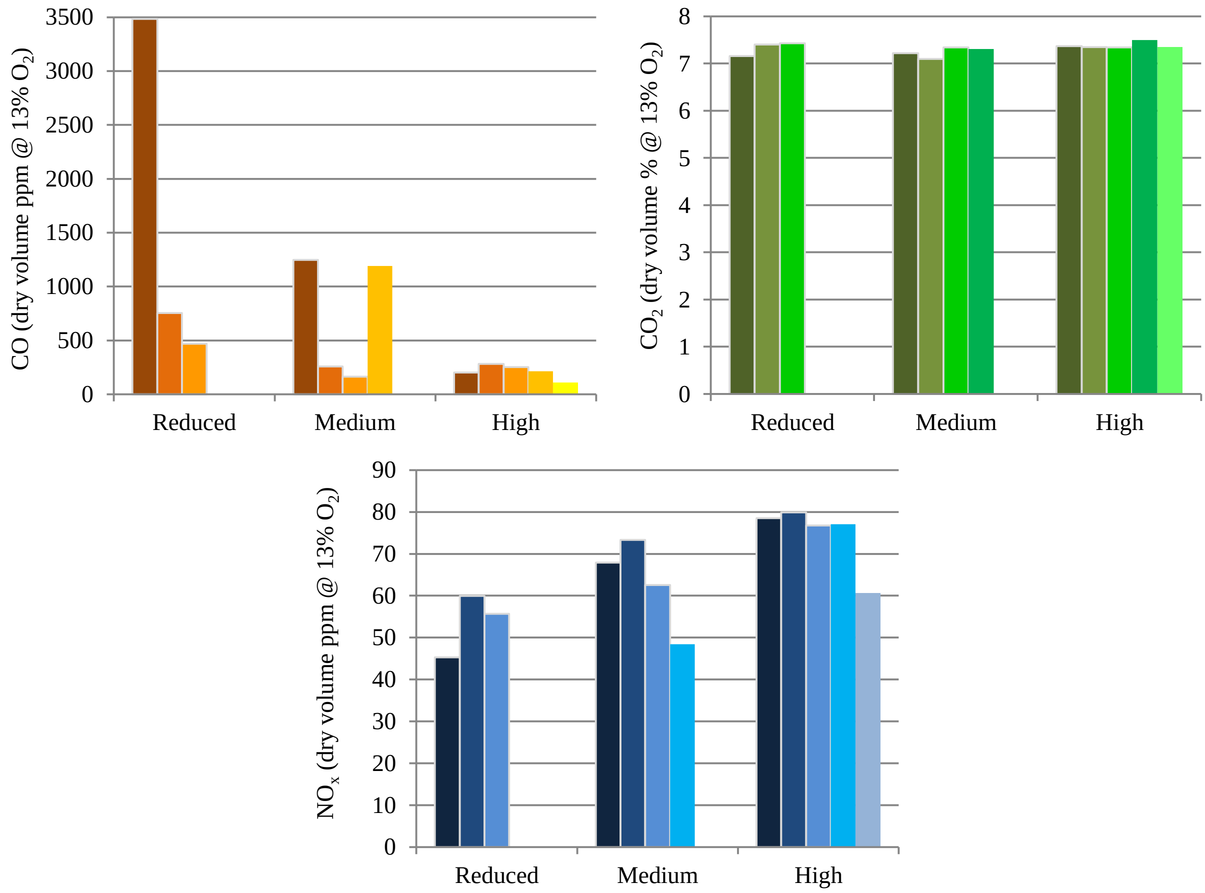

Figure 4. Excess air effect in pollutant emissions.

CO emissions have the opposite trend of boiler's thermal efficiency, regarding excess air influence. High CO emissions are a good indicator of the process inefficiency, being influenced by combustion low temperatures, inefficient fuel and air mixture and short residence time of the flammable mixture in the combustion chamber (Loo e Koppejan, 2008). The increase of CO emissions in test 7 can be explained by low combustion temperature since exhaust gas temperature was much lower (128.07 ºC) in comparison with the other tests in the same load. If the excess air is too low there will not be enough air available to the combustion and if it is too high, the combustion temperature will drop, both situations causing CO emissions increase (Loo e Koppejan, 2008). Merely CO emissions in high load comply with the maximum limits of EN 14785:2006 standard, 600 and 400 ppm @13% O_2, for reduced and high load, respectively.

The influence of excess air in CO_2 emissions is not substantial. In average, those are somewhat higher in high load, where CO's are lower. In reduced load a slight increase is visible; it is also in this load that CO emissions show greater decrease, which suggests that decreasing excess air in these loads promotes less CO and more CO_2.

Three distinct mechanisms cause NO_x formation, fuel, thermal and prompt, but the last two occur in higher temperatures (1300 ºC) and richer mixtures (Loo e Koppejan, 2008). Therefore, fuel-NO_x mechanism is probably responsible for the emissions; however there is an increase pattern from reduced to high load.

3.2 Influence of boiler's insulation

Figure 5 presents the insulation effect in the boiler's thermal efficiency resorting to a comparison between tests performed in the same operation condition (tests 3/14, 6/15 and 12/16).

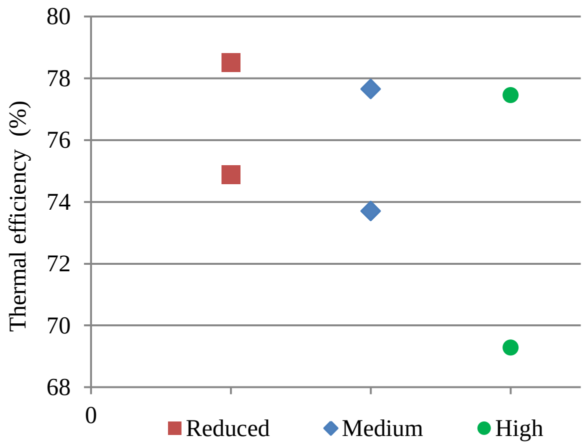

Figure 5. Insulation effect in the boiler's thermal efficiency.

The operation conditions selected to repeat the tests with insulation applied were not only based in maximum thermal efficiency but also in lower CO emissions. The purpose was to increase overall temperatures, including stack gases, to avoid dew point and too high emissions values, exceeding the gas analyzer range.

An increase in thermal efficiency in all loads was registered, with 3.6, 3.9 and 8.2 percentage points in reduced, medium and high load, respectively. The influence of the insulation is more significant in high load, since it is in this load that the combustion temperature is higher inducing greater convection and radiation losses and, consequently, the insulation allows the increase of thermal output.

Regarding pollutant emissions, only in reduced load, which presented the best thermal efficiency, CO emissions were possible to monitor it; in the other loads CO emissions were so high that the analyzer automatically shut off. The optimum point, though probably near, was not explicitly detected as insufficient excess air resulted in very high emissions.

Since the insulation approximated this boiler to a domestic one, the limits of standards were obeyed with both loads concerning thermal efficiency. CO emissions exceeded the limits by far with high loads but respected it in reduced loads.

4. CONCLUSIONS

This study intended to evaluate how reducing excess air on a manufacturer's pre-setup domestic boiler influenced combustion conditions, to obtain the point of maximum thermal efficiency, but not at the expense of pollutants emissions. For that purpose, ENplus certified Pine pellets were burned in three different manufacturer's pre-defined loads and the respective pollutant emissions measured. The initial tests were performed with excess air manufacturer settings, and excess air values were reduced progressively. Later on, the boiler was insulated and new tests were conducted in order to analyze, again, the effect in thermal efficiency and pollutant emissions.

Boiler thermal efficiency was greatly influenced by the decrease of excess air, increasing from 50.06 to 74.88%, 57.89 to 74.51% and 64.44 to 69.29%, in reduced, medium and high load, respectively. The expressive differences suggest that manufacturer excess air settings were too high for the corresponding fuel mass flow rate. The limits established by EN 14785:2006 standard (70% for reduced 75% for high load) were not achieved with manufacturer settings and even in the presence of the lowest excess air values, only is complied in reduced load, which could be related to the fact that these limits are set for insulated domestic boilers.

CO emissions decreased with excess air reduction, which was more evident in reduced and medium load, since in these, the excess air was initially too high for the requirement of air in combustion. On test 7 there was an expressive rise in CO emissions even though the excess air was decreased, due to a low combustion temperature. Concerning the respective standard only CO emissions complied the limits of 400 ppm @13% O_2 in high load, all of the tests in reduced presented higher emissions than 600 ppm @13% O_2. High CO emissions are a good reflex of an inefficient combustion, and this relation was observed in the tests results.

Excess air effect in CO_2 emissions is not significant, only the results in reduced load shows a slight increase in CO_2 accompanied with decreasing CO, even though it is in high load that CO_2 emissions are higher. NO_x formation is not significantly influenced by excess air decrease, but is evident that, in average, the emissions increase in each crescent load. Nonetheless the nitrogen content in the fuel, through the fuel-NO_x mechanism, is the most important factor.

Applying the insulation approximated the lab boiler operation to a domestic use and allowed the increase of the thermal efficiency by 6, 3.9 and 8.2 percentage points in reduced, medium and high load, respectively. It is in high load that the excess air effect is more expressive, as the elevated combustion temperature causes higher convection and radiation losses in the previously non insulated boiler; after the insulation there was an increase in thermal output and, consequently, in thermal efficiency. Regardless, the much greater increase of CO emissions, except in reduced load where they were at its minimum, suggests that for a domestic utilization of this boiler, the excess air values were too low, for the other two loads.

The results of this work indicates that the boiler's thermal efficiency cannot be the only factor influencing the selection of excess air value, the pollutants emitted, in particular CO, have to be also the lowest possible.

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