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# THERMAL PERFORMANCE OF A DOMESTIC BOILER BURNING BRIQUETTES MADE FROM PRUNING WASTES

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**Abstract.** *The thermal performance of a domestic boiler fed with different biofuel briquettes was experimentally evaluated. The biofuels were obtained from vine and kiwi pruning wastes and also pine wood dust.*

*The thermal efficiency of the boiler was determined in steady state operating conditions, either through the direct method or through the indirect method. Only the kiwi briquettes meet the 67.5 % thermal efficiency minimum limit imposed by the EN 12809:2015 standard, applicable to the domestic boiler burning solid fuels.*

*In terms of combustion emissions, no tested fuel respected the 600 ppm limit for the gaseous CO emissions, as defined by the former EN 14785:2008, although as far as the newer EN 12809:2015 is concerned, the carbon monoxide upper limits, 10,000 ppm, were respected by all tested fuels. The briquettes made only with vine pruning wastes, with around 4,400 ppm of CO was the worst performer, namely undergoing a rather slow combustion rate with strong ash release. Mixing it with pine dust, in 5:1 vine to pine proportion, lead to a remarkable combustion performance upgrade, reaching a CO emission reduction of 40 %. The briquettes made only with kiwi fruit pruning wastes, released around 3,500 ppm of CO, presenting a reduction to 970 ppm by heating the boiler feed water.*

**Keywords:** *Biomass, Combustion, Briquettes, Thermal efficiency.*

## 1. INTRODUCTION

Agricultural wastes from the Northern region of Portugal and from Galicia, namely vine and kiwi pruning wastes, were used as fuels in a domestic hot water boiler. Briquettes were produced from these wastes, as such. Briquettes made from vine wastes (80 % w/w) with some pine dust (20 % w/w) were also produced and tested. The vine plant, *Vitis vinifera L.*, is one of the main agricultural products of the Northern region of Portugal and Galicia, and in the case of Portugal it occupies 180,000 ha for winegrowing and 2,000 ha for viticulture and has an enormous historical and socio-economical relevance (INE, 2017). As far as the kiwi plant, *Actinidia deliciosa*, is concerned, Portugal is the fourth large European kiwi producer, behind Italy, France and Greece, with, in 2017, a yearly production of 35,000 t. The estimated cultivated area is about 2,650 ha (Martino, 2019).

The agricultural wastes came from several sources. In the present situation, the pruning wastes under consideration came from winter and summer pruning processes, and for both vegetable species the final destination is commonly the soil, being used as a source of nutrients. In the case of Portugal 2,850 t of such pruning waste is yearly produced per hectare (Freitas, 2014). Typical pruning waste production from fruit trees is of the order of 2 to 5 t of vegetal material per hectare and per year (Terron, 2010).

The biomass is one of the three most important renewable energy sources in Portugal. It can be a dedicated energetic culture, i.e., a fast-growing plant tolerant to biotic and hydric stresses with low demand requirements of soil quality or

agricultural wastes (Panwar *et al.*, 2012; Borkowska and Molas, 2013; Phitsuwan *et al.*, 2013). The mostly cultivated biofuels for energy production around the world are, the eucalyptus (*Eucalyptus spp.*), the poplar (*Populus spp.*), the salix (*Salix spp.*) and non-edible oil plants as the castor (*Ricinus communis*) and the jatropha (*Jatropha curcas L.*). But these energetic cultures have a great disadvantage, they are highly demanding either on irrigation or on natural water (Abbasi and Abbasi, 2010; Ferreira, 2015).

A main limitation concerning the use of biomass for energetic purposes is its low apparent density, increasing transportation and distribution costs (McKendry, 2002a; McKendry 2002b; Nussbaumer, 2003), thus enhancing thermochemical conversion difficulties associated to bad feeding operation leading to low process efficiencies. But through biomass densifying techniques, through the production of biofuel briquettes or pellets, it is possible to minimize or even eliminate such drawbacks (van Loo and Koppejan. 2008; Thek and Obernberger, 2012). The characterization of the biomasses used in the present study is displayed in Tab. 1.

Table 1. Proximate and elemental analysis of the tested fuels.

Fuel	Vine pruning	Kiwi pruning	Pine and vine pruning
Carbon (d.b.) [%]	47.0	46.1	47.7
Hydrogen (d.b.) [%]	6.20	6.60	6.34
Oxygen (d.b.) [%]	46.1	45.8	45.2
Nitrogen (d.b.) [%]	0.60	1.25	0.70
Sulphur (d.b.) [%]	0.05	0.27	0.04
Moisture [%]	10.3	9.90	10.4
Volatile matter [%]	69.5	66.7	70.8
Ashes at 550 °C [%]	3.20	3.50	2.68
Fixed carbon [%]	17.0	19.9	16.1

## 2. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. It is a domestic hot water boiler equipped with several thermocouples, combustion gas analyzers, a Pitot tube in the exhaust combustion gases pipe, all of them connected to a data acquisition system installed in a desktop computer. The data acquisition process was controlled by the DasyLab software. The acquisition rate was of 1 Hz. The boiler is from the Solzaima make, model SMZ IW, and has a nominal thermal power output of 24 kW (Solzaima, 2017; Silva, 2018).

The gas analyzers were:

- An oxygen paramagnetic analyzer from Signal, model 8000M;
- A carbon monoxide infra-red analyzer from ADC, model MGA3000;
- A carbon dioxide infra-red analyzer from Signal, model 7000FM;
- A nitrogen oxides chemiluminescence analyzer from Environnement S.A, model MIR 9000CLD.

The uncertainty values of the experimental measurements are shown in Tab. 2. For the chemical species under consideration the values refer to the corresponding analyzers. For the temperature measurements, three uncertainty values are presented according to the range of measured values, namely for the water temperature, for the exhaust gas temperature and for the furnace temperature.

Table 2. Uncertainty values.

Fuel	[%]
O <sub>2</sub>	±0.1
CO <sub>2</sub>	±0.2
CO	±0.0165
NO	±0.001
NO <sub>2</sub>	±0.001
Water temperature (14 – 40 °C)	±1.90
Exhaust gas temperature (85 – 110 °C)	±1.15
Flame temperature (600 – 950 °C)	±1.10

The boiler is a water tube boiler with an inverted flame fixed bed furnace, with combustion air down flow. The furnace has an upper and a lower chamber. In the upper chamber, incomplete combustion and gasification of the biofuel take place, followed by gaseous phase combustion in the lower chamber. Consequently, the fuel is introduced in the

upper chamber where it dries, suffers incomplete combustion and subsequent gasification. Figure 2 shows a thermographic picture of the boiler under normal operation and the positioning of several thermocouples.

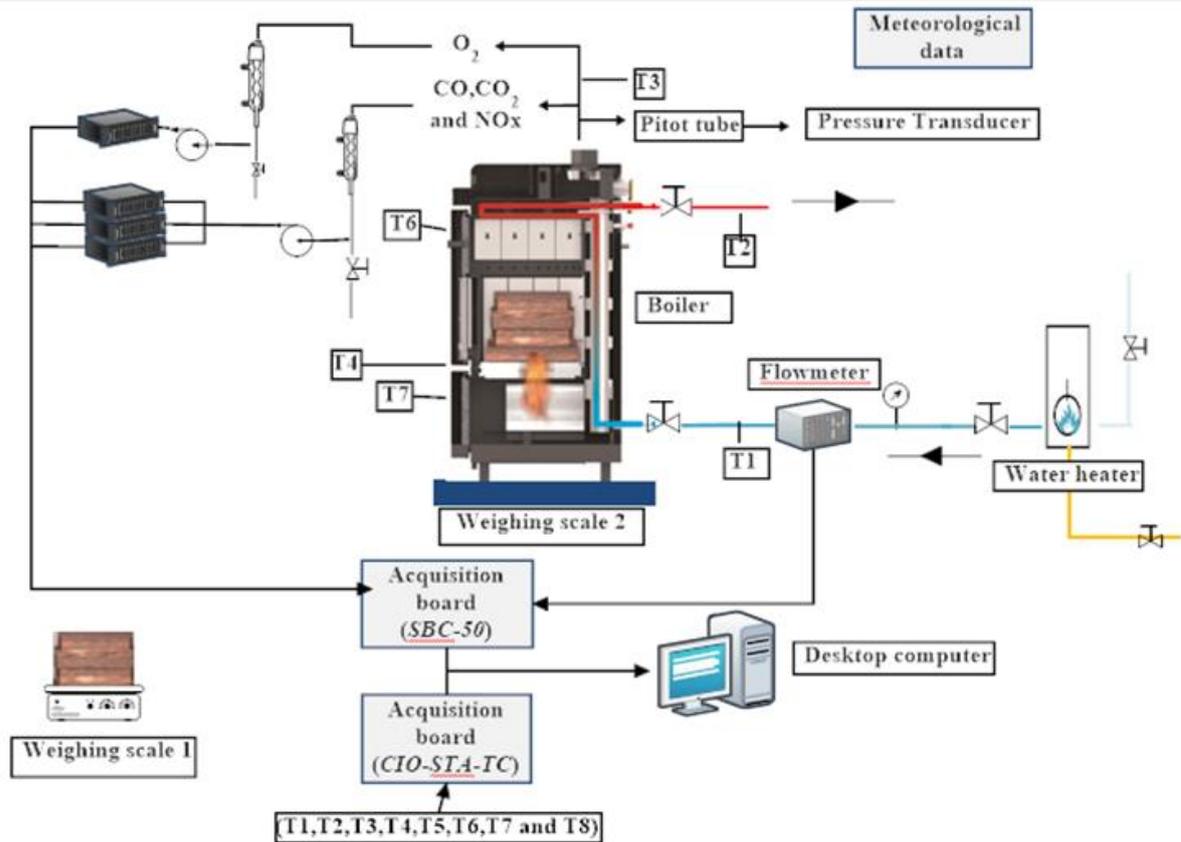


Figure 1. Scheme of the experimental setup.

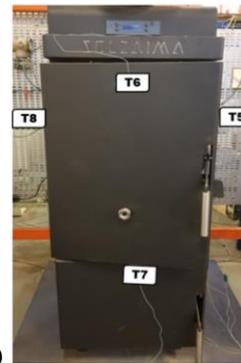
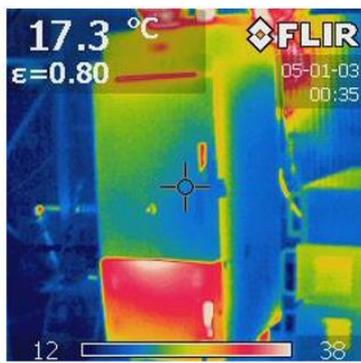


Figure 2. a) Thermographic image of the boiler during a combustion experiment. b) Placement of the thermocouple T4 inside the lower combustion chamber. c) Placement of external thermocouples T5, T6, T7 and T8.

The briquettes were manufactured at the combustion laboratory of INEGI in a hydraulic press from CO.MA.FER, model DINAMOC 70 having a maximum operating compaction press of 570 bar (g). This press produces 55 mm diameter briquettes with a maximum length of 400 mm, starting from sawdust or wood chips with moisture contents in the 8 to 17 % range (w/w) (CO.MA.FER., 2017). The choice of this type of press took into account the many advantages of this briquette manufacturing machine, namely its reliability, lower feeding restrictions and higher rates of production (Tumurulu *et al.*, 2010). Figure 3 represents a scheme of the press operating principle and a picture of the press operating in the laboratory.

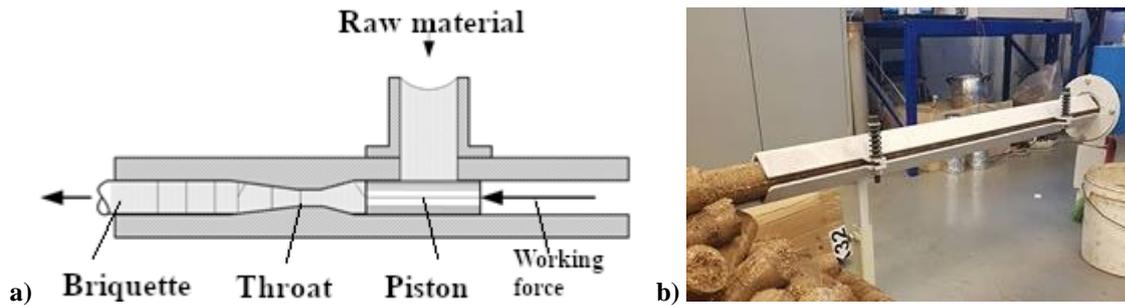


Figure 3. a) Operating principle of the used hydraulic press. b) Picture of the hydraulic press operating at INEGI.

### 3. EXPERIMENTAL RESULTS

The experimental results under analysis concerned the evaluation of the boiler thermal performance as well as the combustion hygiene. Three different types of fuel briquettes were used in the experiments. Briquettes made only with vine pruning waste, briquettes made only with kiwi pruning waste and briquettes made with a mixture of 20 % (w/w) of pine sawdust and 80 % (w/w) of vine pruning waste.

The experiments were carried out with the inlet water at the mains ambient temperature as well as with a water inlet temperature of 40 °C. The first situation (referred as, “amb T”) is more demanding in terms of boiler efficiency performance and combustion hygiene, while the second situation (referred as, “high T”) is closer to the typical operation conditions for this type of boiler. All the experiments were carried out three times.

#### 3.1 Thermal efficiency

For the determination of the boiler thermal efficiency two operating modes of the boiler were considered. In the steady state operating mode about 1 kg of briquettes was fed to the boiler at every 15 minutes, i. e. an inlet fuel flow rate of 4 kg/h. In batch combustion experiments, 3 kg of briquettes were fed at every 45 minutes. In both cases the water mass flow rate crossing the boiler was around 10 kg/min.

The determination of the boiler thermal efficiency was through the direct method, Eq. (1),

$$\eta_t = \frac{\dot{Q}_u}{\dot{Q}_{in}} \quad (1)$$

where  $\dot{Q}_u = \dot{m}_w c_w (T_{w,out} - T_{w,in})$  is the useful thermal power sent to the water and  $\dot{Q}_{in} = \dot{m}_f LHV$  is the input thermal power through the fuel burned.  $\dot{m}_w$  is the water mass flow rate,  $c_w$  is the water specific heat and  $T_{w,in}$  and  $T_{w,out}$  are the water inlet and outlet temperatures.  $\dot{m}_f$  is the mass flow rate of fuel supplied to the boiler and  $LHV$  is its low heating value. In the experimental study, both thermal efficiencies based on the fuel dry and wet basis were determined, although in the present text only dry basis results are considered.

Figure 4 shows the evolution of the boiler thermal efficiency for the steady state operating conditions, while Fig. 5 shows the time evolution of the boiler efficiency for batch operating conditions.

In Fig. 4 evolutions of the thermal efficiency for 120 min periods are presented for several tested conditions. Considering the first 60 minutes of operation, the thermal efficiency is higher for the higher water inlet temperature experiments. However, on the second and final half of the experiments, there are stronger efficiency oscillations and there are no clear distinctions among inlet cooler water experiments and inlet warmer water experiments anymore. Such evolution is understandable, because the boiler gradually warms up and the negative influence of a lower water inlet temperature stops to be significant. Strictly speaking, these experiments are never purely in steady state operating conditions and this explains the superposition of the curves in the last 60 minutes of the experiments.

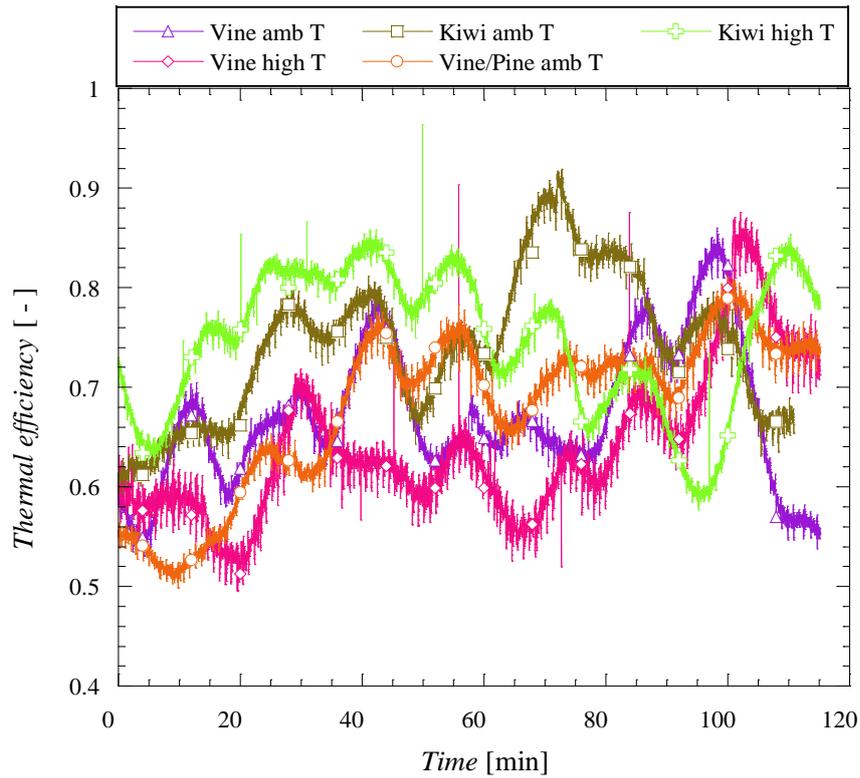


Figure 4. Boiler thermal efficiency for steady state operation.

These steady state experiments with vine briquettes, either with cold or warmer water feeding temperature, show a more stable operation but with lower efficiency, when compared with the kiwi briquettes. However, with these last briquettes, the boiler had efficiencies in the 70 to 80 % range for longer periods, even reaching thermal efficiencies above 90 %, albeit for very short periods. For all the tested briquettes, the periodic-like behavior is connected to the fuel feeding process, during which the furnace door is open for the fuel introduction. This promotes furnace temperature and combustion rate fluctuations, leading to the visible oscillations on the boiler thermal efficiency.

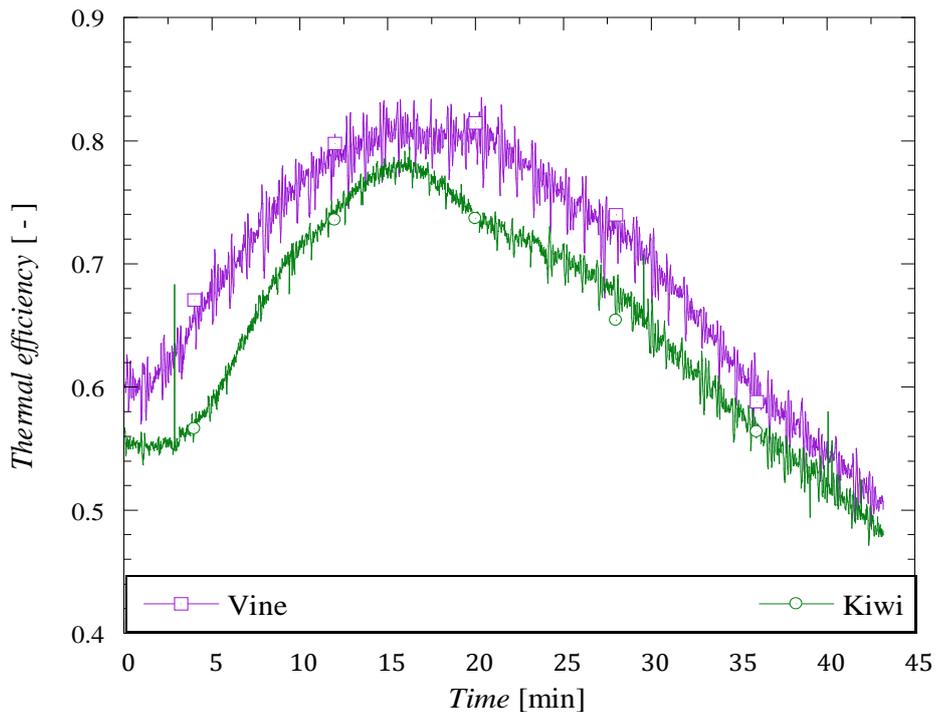


Figure 5. Boiler thermal efficiency for batch operation.

With the batch operating experiments, Fig. 5, it was intended to put the boiler working in a way closer to the real-life operation method, where the users supply a large amount of fuel and then leave the boiler operating unaccompanied for a longer time. These experiments were only done for the warm water inlet temperature conditions.

Contrarily to what was found in the steady state experiments, now the best performance was obtained for vine briquettes, as far as the boiler thermal efficiency is concerned, although the differences in efficiency are of the order of 5 percentage points. The efficiency curves in Fig. 5 show that the boiler needs, after the fuel feeding process, about 5 minutes to reach a stable operating condition with thermal efficiencies above 70 %. The biomass is quickly consumed and after 20 minutes there is an efficiency drop, which means that to keep the boiler operating at higher efficiencies it is necessary to adopt a more frequent fuel feeding procedure.

Only the kiwi briquettes meet the 67.5 % thermal efficiency limit imposed by the EN 12809:2015 standard applicable to the domestic boiler burning solid fuels.

### 3.2 Thermal energy losses

To find out the different fractions of thermal energy losses, these were quantified as unburned gas losses in the combustion exhaust gases  $\dot{Q}_{umb}$ , sensible thermal energy losses in the combustion exhaust gases  $\dot{Q}_{sen}$ , latent heat losses in the in the combustion exhaust gases  $\dot{Q}_{lat}$ , the unburned solids in the ashes  $\dot{Q}_{u,ashes}$  and the other thermal losses  $\dot{Q}_{oth}$ . The unburned gas losses in the combustion exhaust gases  $\dot{Q}_{umb}$  were calculated by,

$$\dot{Q}_{umb} = \dot{m}_{hg} y_{CO} HV_{CO} \quad (2)$$

In Eq. (2),  $\dot{m}_{hg}$  is the mass flow rate of the humid exhaust gases,  $y_{CO}$  is the mass fraction of CO in the humid combustion gases and  $HV_{CO}$  is the heating value of CO. The sensible thermal energy losses in the combustion exhaust gases  $\dot{Q}_{sen}$  where calculated by

$$\dot{Q}_{sen} = \dot{m}_{hg} c_{phg} (T_g - T_{amb}) \quad (3)$$

In Eq. (3),  $c_{phg}$  is the average constant pressure specific heat of the exhaust combustion gases, while  $T_{amb}$  and  $T_g$  are respectively the ambient and the boiler exhaust gas temperature. The latent heat losses in the in the combustion exhaust gases  $\dot{Q}_{lat}$  where calculated by Eq. (4),

$$\dot{Q}_{lat} = \alpha \dot{m}_{fuel} h_{lv} \quad (4)$$

where  $\alpha$  is the fuel moisture content (w/w),  $\dot{m}_{fuel}$  is the fuel mass flow rate and  $h_{lv}$  is the water latent heat of vaporization. The unburned losses in the ashes  $\dot{Q}_{u,ashes}$  were determined through

$$\dot{Q}_{u,ashes} = y_{ashes} \frac{y_{C,fixed} HV_C}{(1 - y_{C,fixed}) LHV_{fuel}} \quad (5)$$

where in this Eq. (5),  $y_{ashes}$  is the fuel ashes mass fraction,  $y_{C,fixed}$  is the fixed carbon mass fraction in the fuel,  $HV_C$  is the carbon heating value and  $LHV_{fuel}$  is the fuel lower heating value. Finally, the other thermal energy losses including convection, conduction and radiation losses  $\dot{Q}_{oth}$  were obtained through the closure of the energy balance.

Figure 6 shows the distribution of the thermal energy losses for the experiments that showed the best thermal efficiencies. The experiments with warmer inlet water present higher sensible heat loses reaching values of 21 % for kiwi burning and 26 % for vine burning. The unburned carbon losses in the ashes have a maximum of 3 % for kiwi burning with warmer water inlet temperature. As far as the unburned CO losses in the exhaust gases were concerned, the maximum was found for vine burning and cooler water inlet temperature.

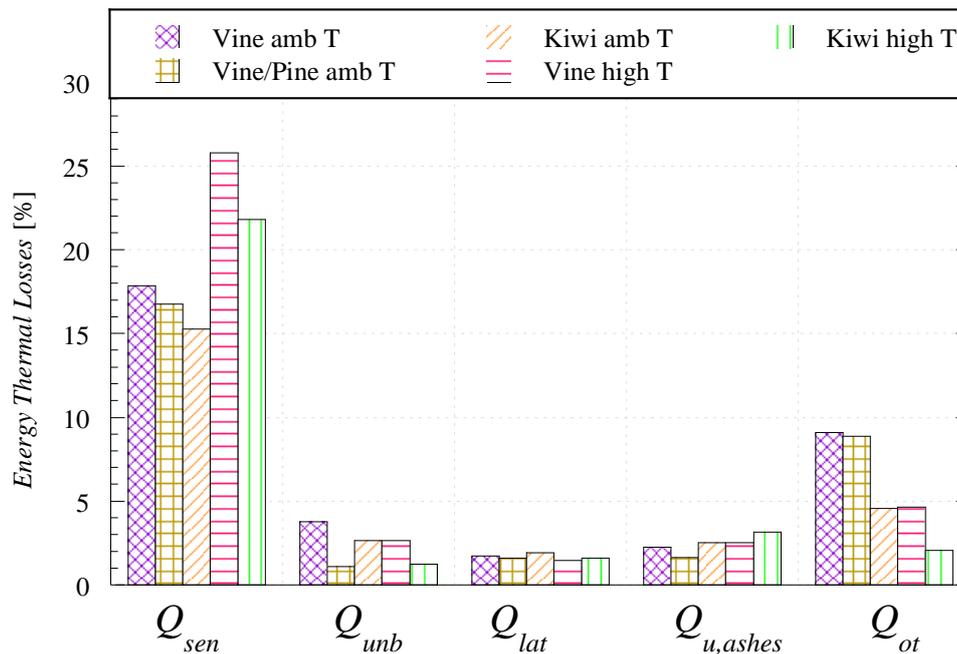


Figure 6. Percentage of thermal energy losses for the experiments that reached the highest thermal efficiency.

### 3.3 Combustion emissions

In this section, the monitored polluting gases and the solid combustion waste were quantified in accordance with the European Standard EN14785:2008, for household heating appliances using wood pellets, which establishes a reference oxygen content of 13 % (v/v).

Figure 7 presents the time evolution of the CO molar fraction corrected for 13 % of O<sub>2</sub>, as well as the boiler exhaust gases temperature  $T_g$  and the flame temperature  $T_{flame}$ . Figure 8 presents the time evolution of CO<sub>2</sub> and O<sub>2</sub> in the exhaust gases, again corrected for 13 % (v/v) of O<sub>2</sub>. These plots are for the boiler steady state operation and for a typical experiment.

The oscillations found, are connected to the furnace opening door and subsequent combustion quenching, during the fuel feeding process. No tested fuel respected the 600 ppm limit (0.06 % v/v, d.b.) for the CO emissions, as defined by the older EN 14785:2008, although as far as the newer EN 12809:2015 was concerned, the carbon oxide upper limits (10,000 ppm = 1 % v/v, d.b.) were respected by all tested fuels. The briquettes made only with vine pruning wastes, with around 4,400 ppm of CO were the worst performer, namely undergoing a rather slow combustion rate with strong ash release. Mixing it with pine dust, in 5:1 vine to pine mass proportion, lead to a remarkable combustion performance upgrade, reaching a CO emission reduction of 40 % (v/v). The briquettes made only with kiwi pruning wastes, released around 3,500 ppm, presenting a reduction to 970 ppm by heating the boiler feed water, instead of feeding the boiler with cold water.

Because the boiler operated with high excess air values, the corresponding furnace temperatures were very low, the NO formation mechanism was the fuel-NO (Glassman, 1996; Borman and Ragland, 1998). Accordingly, the kiwi pruning waste lead to the highest NO emissions. The NO emissions were always in the 100 to 200 ppm (v/v, d.b.) range, while the NO<sub>2</sub> values were meaningless, between 10 and 12 ppm (v/v, d.b.).

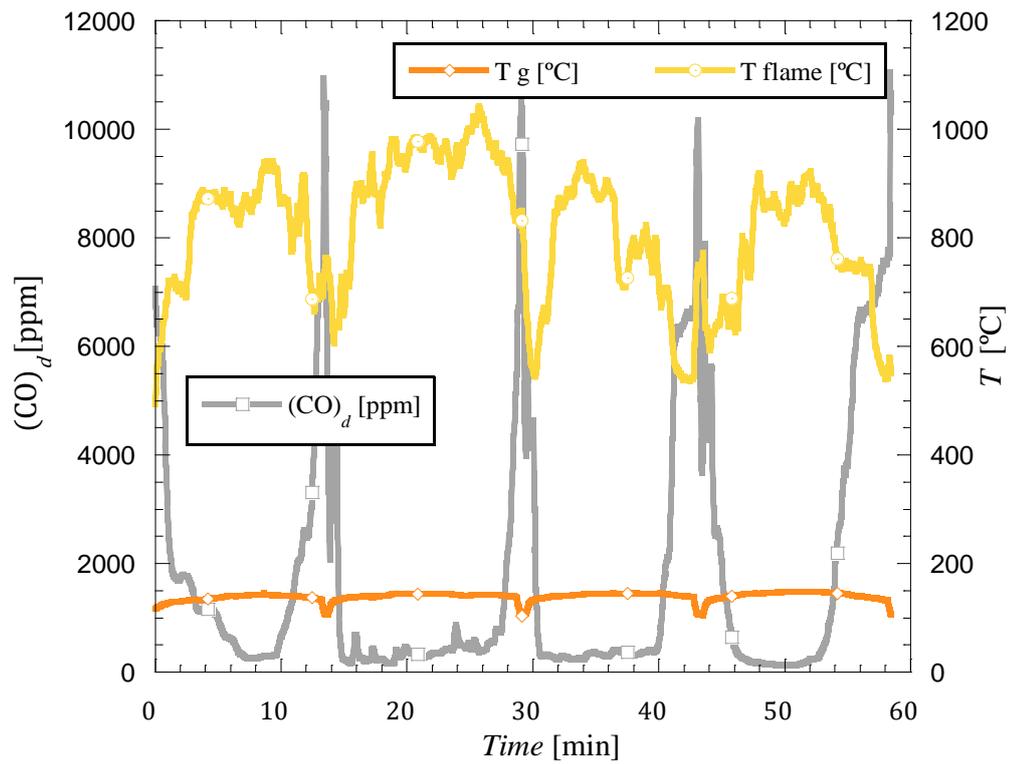


Figure 7. Time evolution of CO molar fraction, flame and exhaust gas temperatures.

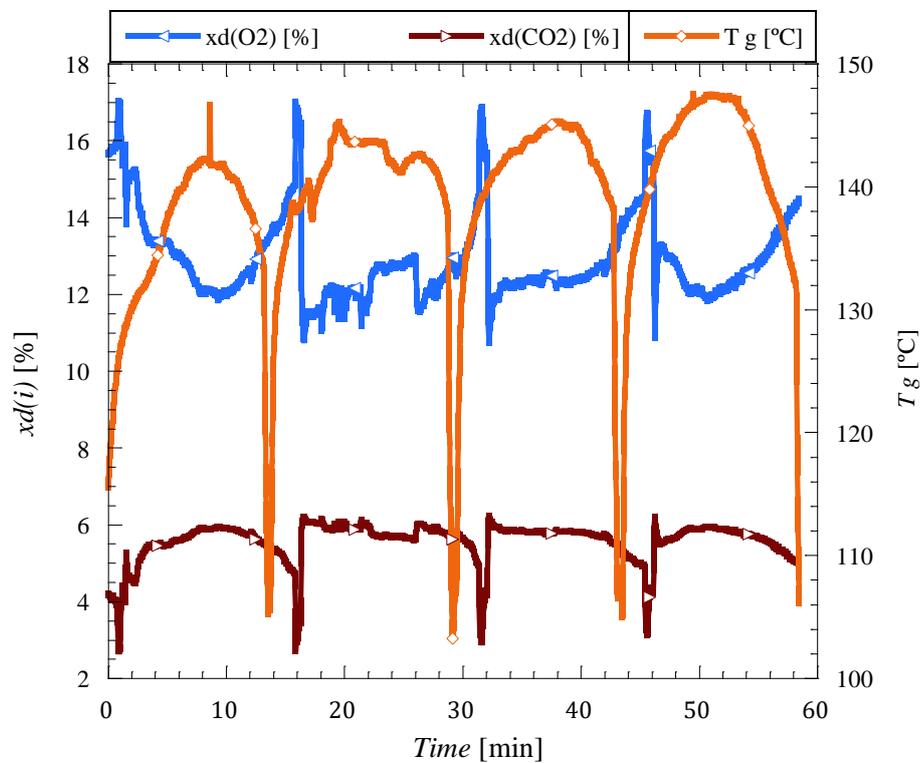


Figure 8. Time evolution of O<sub>2</sub> and CO<sub>2</sub> molar fraction and exhaust gas temperature.

#### 4. CONCLUSIONS

The main objective of the present work was the study of the thermal performance of a domestic briquette burning boiler operating. The briquettes were fabricated with agricultural wastes, vine and kiwi pruning wastes and pine sawdust. The combustion experiments were carried out in approximately steady state conditions.

The kiwi made briquettes presented a better thermal efficiency performance with the best values in the 70 to 80 % range, while the vine made briquettes were always behind in terms of the boiler thermal efficiency. Only by mixing 80 % (w/w) of vine pruning waste and 20 % (w/w) of pine sawdust, a thermal efficiency of 70 % could be reached. Consequently, only the vine briquettes meet the 67.5 % thermal efficiency minimum limit imposed by the EN 12809:2015 standard applicable to domestic boilers burning solid fuels.

These efficiency values were determined by the direct method. Through the indirect method, a hierarchy of the thermal energy losses of the boiler could be established, being the sensible thermal energy of the exhaust combustion gases the main loss.

As far as the carbon monoxide emissions were concerned, the vine waste presented the highest values and showed a reduction from 0.44 % (v/v, d.b.) to 0.24 % (v/v, d.b.) with the increase of the boiler feed water temperature, and a reduction towards 0.16 % (v/v, d.b.) through the addition of pine sawdust. The kiwi got a reduction from 0.35 % (v/v, d.b.) to 0.097 % (v/v, d.b.) with the increase of the boiler feed water temperature, the best result obtained in all experiments.

Because the boiler operated with high excess air values, the corresponding furnace temperatures were very low, so the NO formation mechanism was the fuel-NO, based only on the fuel composition, presenting a vestigial contribution in the gaseous emissions. The NO emissions were always in the 100 to 200 ppm (v/v) range, while the NO<sub>2</sub> values were between 10 and 12 ppm (v/v, d.b.).

#### 5. ACKNOWLEDGEMENTS

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