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PELLETS COMBUSTION IN A SMALL SIZE BURNER: PERFORMANCE EVALUATION

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Abstract. The objective of this work is to evaluate the combustion performance of commercial pellets in a small size burner, which may represent a scale model furnace operating with residual biomass pellets. Tests are for three different commercial pellets produced from woody and non-woody origin: peanut husk (NWB-01) and pinewood (WB-01 and WB-02), from two different manufacturers. Combustion quality is assessed and comparison of combustion indices obtained through different methodologies: i) index based on *test time, temperature and mass-consumption*; ii) *index based on TGA parameters*; iii) *non-dimensional combustion indexes, as an innovative proposal in this work*. Data acquisition for experimental parameters allows to calculate and compare the combustion performance, and includes measuring for: mass-consumption variation through a load cell, K-type thermocouples, data acquisition system by a micro-controller board in the Arduino platform. Main conclusions are : as duas metodologias para o cálculo dos índices de combustão não tiveram resultados parecidos; Three of the proposed adimensionals had the same behavior as the index calculated based on the methodology using the TGA parameters. The pellet that obtained the highest combustion index according to this methodology was Pine 1, followed by Pine2 and peanut husk.

Keywords: *renewable energy, residual biomass, combustion indexes, torrefaction.*

1. INTRODUCTION

In the face of environmental concern and firewood scarcity, it is necessary to search for renewable energy sources, especially when the world demand for energy is observed. The reduction of energy resources of fossil origins, coupled with the emergence of new sustainable technologies, encouraged the study of biomass as a source of energy, creating alternatives for its use (Lima et al, 2016). Biomass is a cellulosic material that can be widely classified as woody and non-woody biomass, woody biomass can be further divided into soft and hard ones (Borman, 1998).

In this environment protection scenario, and aiming at reducing energy waste, the use of solid biofuels, such as those originating from residual biomass, can replace fossil fuels in whole or in part (e.g. mineral coal, shale, etc.). This would allow reducing greenhouse gas (GHG) emissions. The use of fossil fuels (or non-renewable) is largely responsible for the emission of pollutants and has increasingly impaired the environment, thus researches in the area of renewable energy sources are highlighted in the scientific community (Silva et al., 2016). The use of biomass as fuel has been widely used due to environmental reasons (conversion of biomass into energy products with an acceptable environmental impact) or economic (alternative to fossil fuels) (Sánchez, C., 2010).

The objective of this work is to evaluate the combustion performance of commercial pellets in a small size burner, which may represent a scale model furnace operating with residual biomass pellets. Combustion quality is assessed and comparison of combustion indices obtained through different methodologies. Data acquisition for experimental parameters allows to calculate and compare the combustion performance.

2. METHODOLOGY

Samples for three different commercial pellets, residual biomass produced from woody and non-woody origin: peanut husk (NWB-01) and pinewood (WB-01 and WB-02), from two different manufacturers, as indicated in Figure 1.

Pellets density determination is as follows: a) 20 units sample was weighed; b) Measuring diameter and length, to volume calculation; c) the resulting values are: $\rho_{\text{NWB-01}} = 950 \text{ kg.m}^{-3}$; $\rho_{\text{WB-01}} = 1029 \text{ kg.m}^{-3}$; $\rho_{\text{WB-02}} = 1195 \text{ kg.m}^{-3}$. Thermal conductivity C_p ($\text{J.kg}^{-1}.\text{K}^{-1}$) determination uses a bomb calorimeter (KL-5 type, thermometer precision 0.005°C), by using the ratio between the heat of combustion (HHV, J.kg^{-1}) and water's temperature variation (ΔT , K).

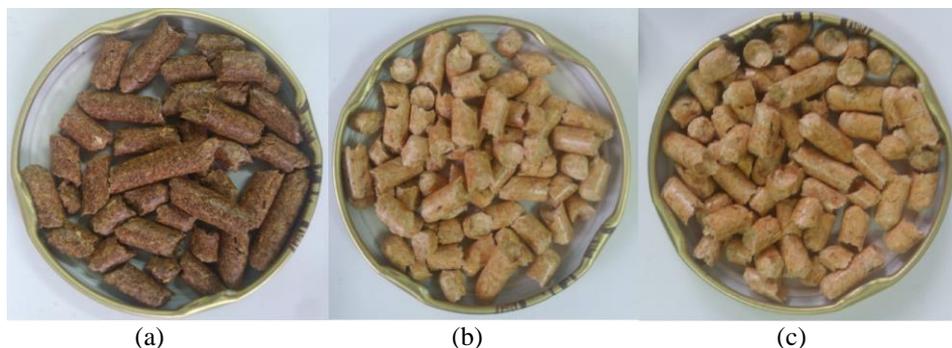


Figure 1. Commercial pellet samples: (a) NWB-01, (b) WB-01, and (c) WB-02.

2.1 Proximate Analysis and HHV

Experimental determination for HHV is according to NBR 11956 (ABNT, 1990), through a calorimeter (PARR, model 6400). Proximate analysis is according to NBR 8112 (ABNT, 1986), providing contents for MC_{wb} and db (%), VM_{db} (%), FC_{db} (%), ASH_{db} (%). The following equipments were used for proximate analysis experiments: Muffle furnace (Fornitec – maximum temperature 1200°C); Muffle furnace (Magnus – maximum temperature – 1000°C); Analytical Scale (Shimadzu, ATY 224, 0–220g range and ± 0.0002 uncertainty) and a stove (Lucadema 80/30 – 250°C maximum temperature).

2.2 Experimental test apparatus, data acquisition and procedure

Figure 2 represents the test apparatus, where experiments are carried out. The combustion process is carried out in a small size burner (1) - biomass combustor, with cylindrical shape to represent a scale model furnace; 121mm length and 100mm diameter. In positions (2) and (3), there are both in the radial direction, air inlet (19.5 mm height and 67.5 mm width, 1316.25 mm^2 ; as total area) and an opening for grill device insertion, respectively. In this work, no airflow measurement occurs (no air-fuel ratio available), and only one grill shape is under tests with a total airflow area of 1446.52 mm^2 , corresponding to $\sim 19\%$ of the total surface area ($\varnothing 4.5 \text{ mm}$ and 91 holes, drilled in the grill surface). Other elements are: (4) is for position thermocouples positioning, universal bracket (base + stems); (5) is the load cell; (6) are positions for both thermocouples, T1 at the pellets and T2 positioned 50mm above the grill.

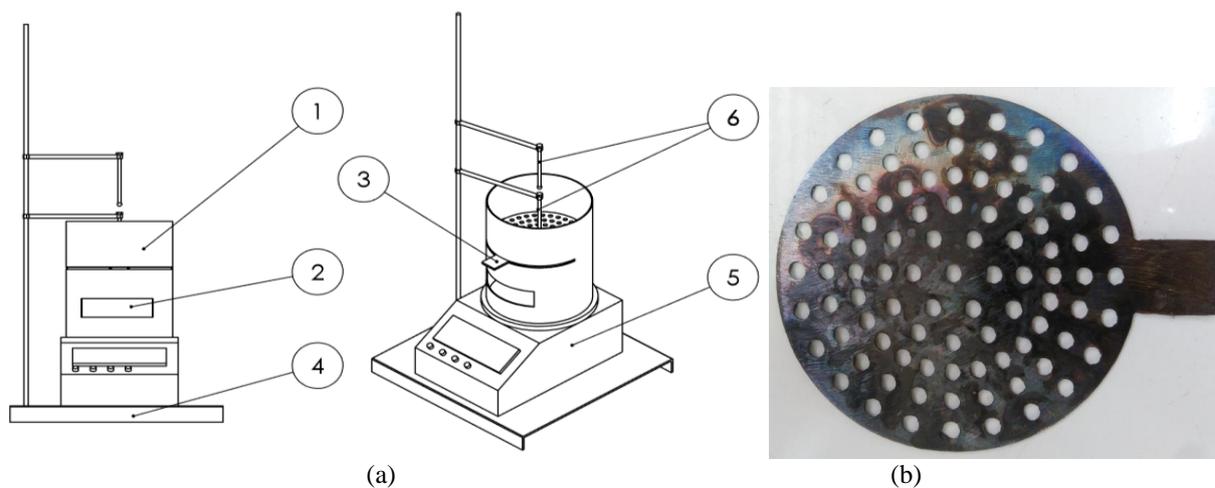


Figure 2. Experimental apparatus: (a) set-up; (b) grid detail

Data acquisition for the following experimental parameters allows to calculate and compare the combustion performance: load cell for mass variation during combustion process (0-5 kg measuring range, 1g resolution), K-type thermocouples (-200°C up to 1260°C measuring, $\pm 2.2^\circ\text{C}$ or 0.75% as uncertainty; Figliola and Beasley, 2007), and

data acquisition system by a micro-controller board (ATMEGA2560) in the Arduino platform. Load cell and thermocouples were attached to the DAQ system with recordings for mass (Δm , g) and temperature (ΔT , °C) at each $\Delta t = 5s$.

Each test run considers ~17.40 g of pellets as total mass at test beginning. To ensure the solid fuel ignition, a small amount of liquid fuel is available under the grill (~3.48 g of Alcohol, 92.8% vol), just bellow position (2) in Fig. 1. natural convection provides air for the combustion process; that corresponds to obtaining non-premixed flames (or diffusion flames), i.e., initially separated fuel and oxidant, and the combustion occurring in the interface between them (Carvalho Júnior et al., 2018).

2.3 Combustion indexes determination

Three different methodologies were considered in this work to evaluate the combustion quality. Two of them take into account different parameters for combustion indexes calculation from literature. The third one is a proposition under evaluation in the present work which takes into account non-dimensional analysis for parameters which are important to define the solid fuel energy content and ability to “easy combustion” and parameters for the combustion process itself.

2.3.1 Index based on test parameters: time, temperature and mass-consumption (Quirino, 1991)

Briquettes burning in a small burner is a methodology that is available for plenty of residual biomass analysis, and it is originally proposed by Quirino (1991). In here, naming it as “ Q_{index} ”, Eq. (1), that combustion index proposes to quantify the combustion process using reference temperatures achieved and fuel mass consumed.

$$Q_{Index} = (A \cdot B) / (C \cdot 100) \quad (1)$$

Where:

- A= Percentage (%) of the test time at which the temperature remains higher than T_{Ref} ;
- B= Percentage (%) of the maximum temperature reached in the tests, higher than T_{Ref} ;
- C= Percentage (%) of total mass-consumed which generates $T > T_{Ref}$.

In here, T_{Ref} corresponds to ~65% of the maximum temperature reached during the combustion of the pellets (T_1 recordings); the lowest T_{Max} between the three pellets samples were considered. It corresponds to adaptations in the original methodology, which evaluated the combustion blended briquettes manufactured from biomass, coal/charcoal (up to 37% of ash content) and other elements to improve combustion (ex: sodium nitrate), from Brazilian, EUA and Argentina origin, and considered $T_{Ref} = 150$ °C (Quirino, 1991).

2.3.2 Index based on TGA parameters (Xiang Gu et al., 2006)

Thermogravimetric results, by TGA analyzer provides the behavior of the pellets for a predetermined heating rate. Using DTG results, the first derivative of the TGA curve, it is also possible to obtain the rate of mass loss in time, and can identify the combustion stages. The pellets samples were crushed and sifted into a sieve with mesh 35 (0.5mm of aperture) as input in TGA analysis; using atmospheric air at a flow of 100 mL.min⁻¹, and ~10 mg for each sample; the heating rate was 10°C.min⁻¹, starting at 30°C and warming up to 600°C.

Data from TGA results also can be used to obtain a combustion index, S in Eq. (2), as indicated by Liu et al. (2013) and in other literature works (Protásio et al., 2017; Qian et al., 2012; Moon et al., 2013).

$$S = [(dm / dt)_{max} \cdot (dm/dt)_{average}] / (T_i \cdot T_f) \quad (2)$$

Where:

- $(dm / dt)_{max}$ = is the maximum combustion rate (%.min⁻¹);
- $(dm / dt)_{average}$ = is the mean combustion rate (%.min⁻¹);
- T_i = is the ignition temperature (°C);
- T_f = is the burnout temperature (°C).

Furthermore, the ignition rate ($D_{ignition}$) can be obtained by the Eq. (3), as also pointed out in literature (Protásio et al., 2017; Xiang Gu et al., 2006).

$$D_i = (dm / dt)_{max} / (T_p \cdot T_{ig}) \quad (3)$$

Where:

T_p = is the corresponding time at which occurs the maximum combustion rate (min);
 T_{ig} = is the time when the ignition occurs (min).

The ignition temperature is defined as the minimum temperature for the fuel to spontaneously ignite without an external source of energy; this temperature can be determined using the TGA through the intersection method (Lu, J. and Chen, W., 2015). This method consists on identifying two points in a TGA curve, see Figure 3: “A” is the position where from a vertical line traced from the highest point of the DTG line through the TGA curve; “B” is the time instant where the devolatilization initiates. Thus, tracing a tangent line in TGA curve and another horizontal line from position “B”, the temperature corresponding to the intersection of these two lines is identified as $T_{ignition}$ (Lu, J., Chen, W., 2015). As for “C” position, it corresponds to the location there DTG’s second peak crosses the TGA curve; while “D” position is where the TGA curve remains constant. The burnout temperature (T_f) is obtained by the intersection of a tangent line (between “C” and TGA curve) and a horizontal line passing trough “D” position (Lu, J., Chen, W., 2015).

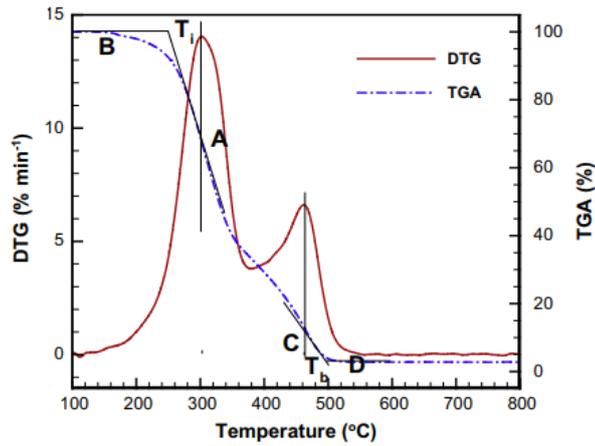


Figure 3. Ignition and burnout temperatures determination (Lu, J. and Chen, W., 2015)

2.3.3 Non-dimensional combustion indexes

An innovative proposal in this work is to look for combustion indexes as non-dimensional numbers. Thus, a set of parameters that could be adequately measured in experiments to apply the Buckingham PI's theorem methodology (Fox, Pritchard, and McDonald, 2010). In that first approach, 8 (eight) parameters were selected: a) four non-repetitive variables, HHV ($J.kg^{-1}$) – High Heating Value, ρ ($kg.m^{-3}$) – density, TP (W) – Thermal Power, and C_p ($J.kg.K^{-1}$) – specific heat; b) four repetitive variables, T_{Max} (K) – maximum temperature reached in tests, R_{Time} (s) – a reference time in tests at which occurs T_{Max} , A (m^2) – grid reference area, and m (kg) – solid fuel mass (pellets sample). The following non-dimensional numbers result from that approach:

$$\pi_1 = [HHV \cdot (R_{Time}^2)] \cdot (A)^{-1} \quad (4)$$

$$\pi_2 = [\rho \cdot (A^{3/2})] \cdot (m)^{-1} \quad (5)$$

$$\pi_3 = [TP \cdot (R_{Time}^3)] \cdot (m)^{-1} \quad (6)$$

$$\pi_4 = [C_p \cdot T_{Max} \cdot (R_{Time}^2)] \cdot (m)^{-1} \quad (7)$$

3. RESULTS AND DISCUSSION

Proximate analysis and HHV for test pellets are in Table 1. Those pellets are in natura conditions (as commercialized in the market), present low moisture content 7-9% as other solid fuels (typically <10%); wood artificial drying through thermal processes reach 8-12%, while wood logs in natural drying reach 40-55% (Rendeiro, 2008). As for the volatile matter, those pellets present higher content ($VM_{db} > 75\%$), as in comparison to rice husk (~65-69%) and Angelim wood (~70%) (Rendeiro et al., 2008; Sánchez, 2010). Pellets HHV (~ 19 MJ.kg⁻¹) are slightly higher than other firewood samples, for example, HHVPine-firewood = 18.8 MJ.kg⁻¹ (Vlassov, 2001); HHVNWB-01 is the higher among pellets test samples, probably due to its carbon content that reaches FCNWB-01 ~20.5%. High amounts of ash content are undesirable, once ash deposition on heating surfaces can cause fouling and corrosion, resulting in reduced heat transfer efficiency, increased operating and maintenance costs, and high rate of Accidents (Song et al., 2018).

Table 1. Proximate analysis and HHV for commercial pellets samples.

	MC _{wb} (%)	VM _{db} (%)	FC _{db} (%)	ASH _{db} (%)	HHV (MJ.kg ⁻¹)
NWB-01	8.43	76.88	20.47	2.65	19.44
WB-01	6.86	83.55	16.23	0.23	19.11
WB-02	7.87	82.85	16.66	0.49	18.61

Typical reference stages for solid fuels combustion process are in Figure 4. They are: (a) Ignition ($\Delta t = 20$ s), alcohol assisted; (b) Self-sustained combustion ($\Delta t = 145$ s); (c) After burnout ($\Delta t = 215$ s). In the first stage, flame occurs only bellow the supporting grid; while in the last stage, after flame burnout, there is a visualization of red and hot charcoal. At the middle stage, flames visualization is clear and intense, reaching high positions beyond the external thermocouple (50mm above grid).

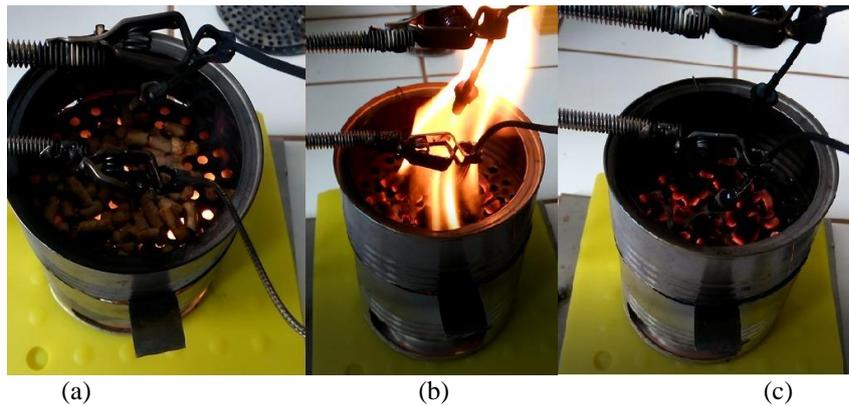


Figure 4. Combustion test main stages at the experimental apparatus (W-01 pellets samples).

Figure 5 indicates, for two fixed positions, the temperature behavior in combustion tests. Horizontal line ($T = 353^{\circ}\text{C}$, “black”) represents the reference temperature for one of the combustion indexes calculation (T_{ref} , see methodology section). Vertical line ($\Delta t = 76$ s, “blue”) corresponds, approximately the combustion first stage ending (alcohol assisted ignition), while the other vertical line ($\Delta t = 585$ s, “green”) indicates the test ending criteria, and corresponds to the time instant when the load cell stops registering significant mass variation (from $t_{585\text{s}}$ up to $t_{1000\text{s}}$, $\Delta m \sim 0.8\text{g}$, which corresponds to $< 5\%$ of original mass sample); $\Delta m < 1$ g, i.e., lower than measurement resolution). Due to flame front positioning, temperatures are higher in T2 (Fig. 5b) in comparison to T1 (Fig. 5a). Temperatures increases until time range $\Delta t = 153\text{-}220$ s (corresponding to 19.1-27.5% of the total test time, $\Delta t = 800$ s), with the following maximum values occurring for pellets combustion: $T_{\text{Max-NWB-01}} = 567.0^{\circ}\text{C}$, $T_{\text{Max-WB-02}} = 571.0^{\circ}\text{C}$, and $T_{\text{Max-WB-01}} = 618.5^{\circ}\text{C}$, which are in the same order than FC_{db} content (or inverse order for VM_{db} content, see Table 1). While thermocouple 1 (Fig. 5a) maximum temperatures are: $T_{\text{Max-NWB-01}} = 528.5^{\circ}\text{C}$, $T_{\text{Max-WB-02}} = 530.0^{\circ}\text{C}$, and $T_{\text{Max-WB-01}} = 553.0^{\circ}\text{C}$. Maximum test temperature occur in different time instants for both thermocouple position, nevertheless, differences are: $\Delta T_{\text{Max-NWB-01}} = 38.5^{\circ}$, $\Delta T_{\text{Max-WB-02}} = 18.5^{\circ}\text{C}$, and $\Delta T_{\text{Max-WB-01}} = 88.0^{\circ}\text{C}$.

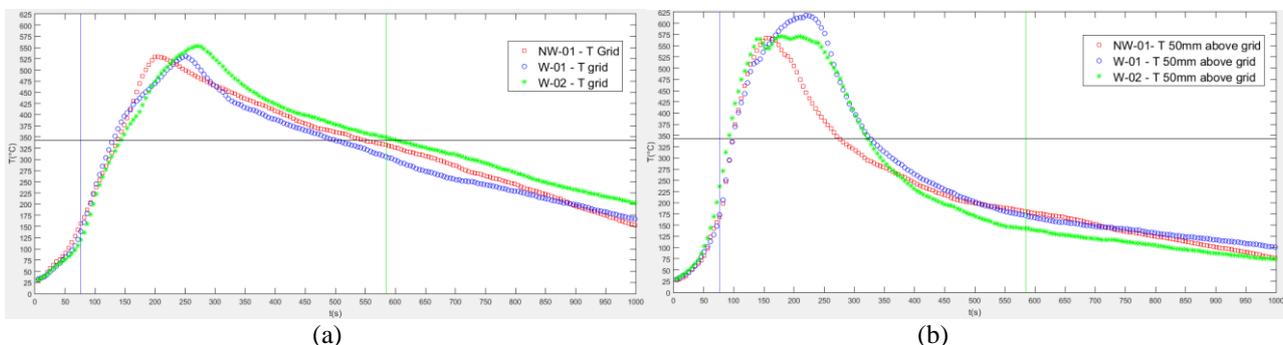


Figure 5. Temperature behavior in combustion tests - Thermocouple position: in the grid (a); above the grid (b).

Fuel mass decreases as combustion test goes on, as pointed out in Figure 6. Up to $\Delta t = 76$ s (vertical line, “blue”) there are solid and liquid fuels, i.e., pellets and alcohol (assisted ignition). In Figure 6(b), a zoom visualization ($\Delta t = 75\text{-}250$ s) is available for better assessment and discussion on combustion behavior and fuel mass consumption. In that time range, a great mass consumption occurs in a short time: $\Delta m_{\text{WB-01}} = 78.4\%$, $\Delta m_{\text{WB-02}} = 73.6\%$, and $\Delta m_{\text{NWB-01}} = 66.4\%$; and significant slopes: $(\Delta m / \Delta t)_{\text{WB-01}} = 0.45 \text{ \%}\cdot\text{s}^{-1}$, $(\Delta m / \Delta t)_{\text{WB-02}} = 0.42 \text{ \%}\cdot\text{s}^{-1}$, $(\Delta m / \Delta t)_{\text{NWB-01}} = 0.38 \text{ \%}\cdot\text{s}^{-1}$. Notice that

$(\Delta m / \Delta t)$ increases as high is the FC_{db} content (or as low is VM_{db} content, see Table 1), a similar behavior also pointed out for T_{max} in the flame front (Fig. 5B, T2).

After test ending ($\Delta t = 585$ s), load cell starts to record oscillating mass values, that are spurious data which must be neglected. At that condition, there are remaining solid fuel mass (unburned pellets) and ashes: $m_{WB-01_unburned} = 1.40g \pm 1.0g$ (or $4.8\% \pm 4.8\%$), $m_{WB-02_unburned} = 1.03g \pm 1.0g$ (or $8.0\% \pm 4.8\%$), $m_{NW-01_unburned} = 0.82g \pm 1.0g$ (or $5.9\% (\pm 4.8\%)$). Those values indicate that combustion process is incomplete ($m_{unburned} > ASH_{db}$), probably due to low availability of air/O₂; thus, in future tests an interesting modification on the experimental apparatus is to include inlet air by forced convection to obtain complete combustion ($m_{unburned} \sim ASH_{db}$).

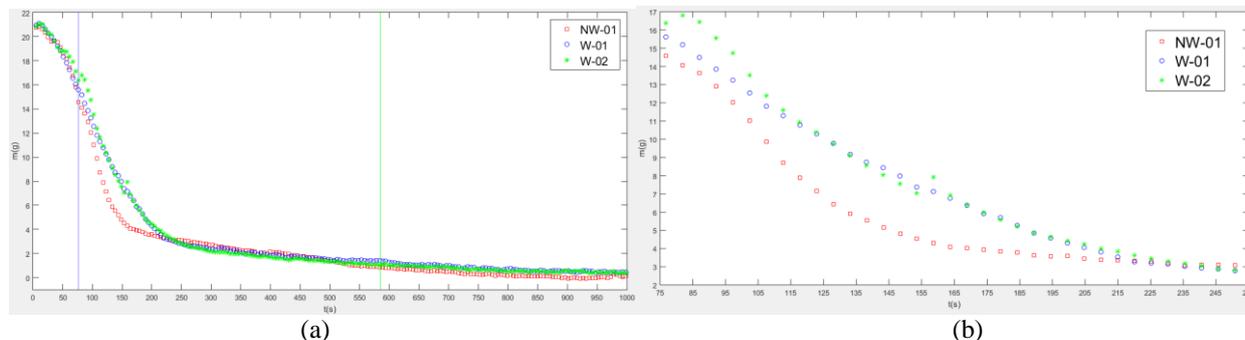


Figure 6. Fuel mass consumption in combustion tests.

Comparison for combustion quality assessment, for solid fuels, is through 3 (three) different methodologies. First results are for Q_{Index} determination, in Table 2; next, Table 3 with indexes based on parameters from TGA and DTG analysis (Figure 7); and then, non-dimensional numbers in Table 4. The Q_{Index} approach (Tab. 2), indicates the decreasing combustion quality in the following order: at $Q_{Index_W-02} > Q_{Index_NW-01} > Q_{Index_W-01}$. Other literature results for Q_{Index} determination range from 0.31-1.23 for briquettes samples (coal+biomass; Quirino, 1991), and from 1.57-2.10 for grinding biomass (Eucaliptus, Crambe and Bocaiúva; Silva et al., 2016) Different orders of magnitudes probably are due to almost punctual parameters definition on Q_{Index} calculation, which strongly depends on dimensional parameters, as T_{Ref} temperatures can be quite higher or lower, according the biomass sample condition, varying from sawdust, to pellets or briquettes.

Table 2. Parameters for Q_{Index} determination.

	W-01	W-02	NW-01
$\Delta t_{T > T_{ref}}$ (s)	586	586	586
T_{Max} (°C)	530.0	553.0	528.0
$\Delta m_{T > T_{ref}}$ (g)	16.017	16.322	16.452
A (time fraction, %)	62.28	75.44	69.30
B (temperature fraction, %)	154.43	161.13	153.84
C (mass consumption fraction, %)	92.00	94.10	95.22
Q_{Index}	1.045	1.292	1.119

Analyzing TGA and DTG results (Figure 7), the following applies: a) Cellulose and hemicellulose decomposition occurs in a temperature range ($\Delta T = 180-340^{\circ}C$), when DTG values are maximum and TGA slope goes down, those temperatures conditions represent VM ignition, which generate CHARCOAL (López-Gonzales, et al., 2013). Temperatures when DTG values are maximum at a second condition (DTG_{2nd_peak}) correspond to the CHAR/CHARCOAL oxidation, with lignin being the main responsible for that CHAR formation (López-Gonzales, et al., 2013).

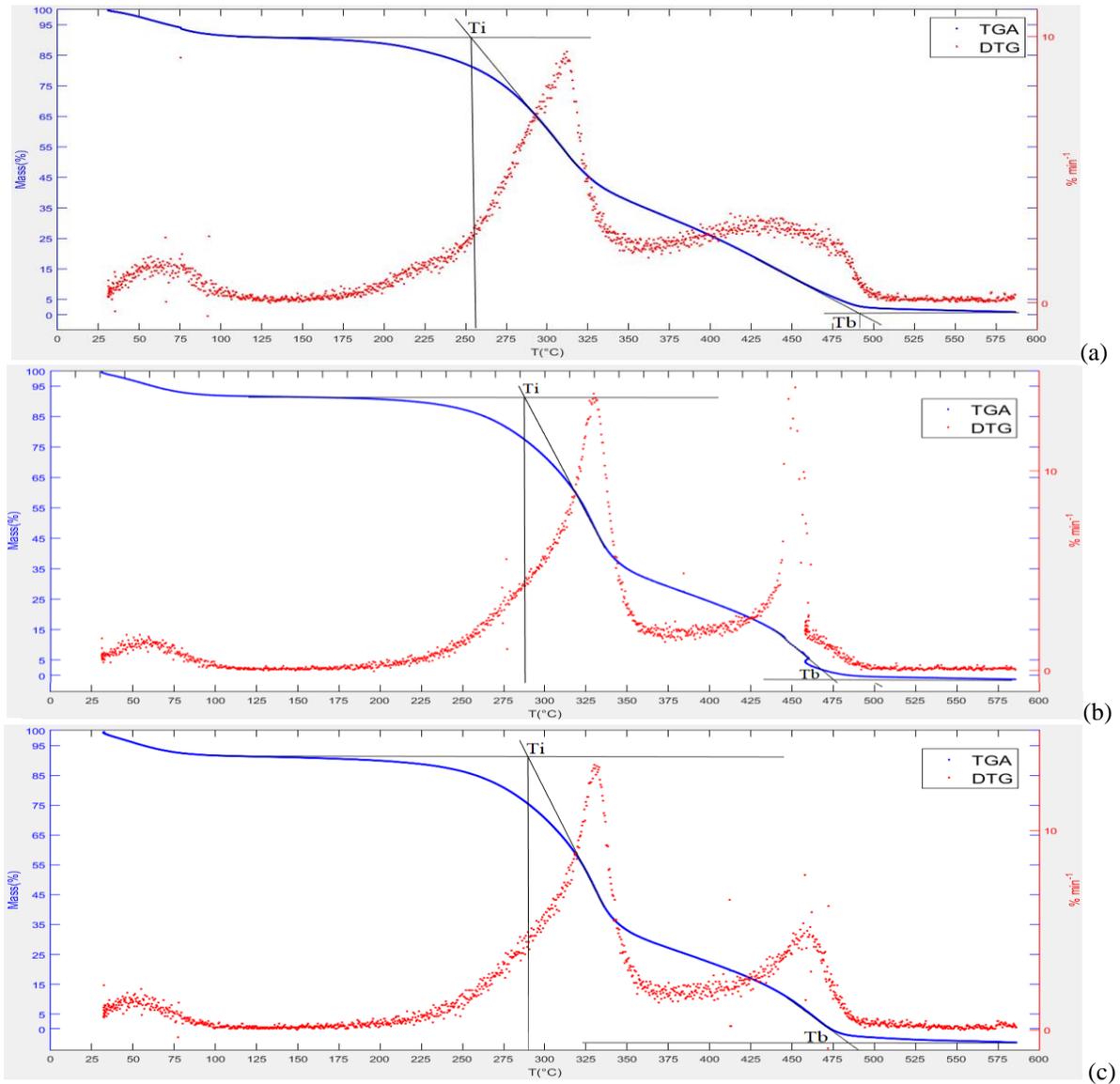


Figure 7. TGA and DTG analysis: NW-01 (a), W-01 (b), and W-02 (c).

Determination for S_{Index} and $D_{Ignition}$ (Tab. 3) are possible after TGA and DTG analysis (Fig. 6), respectively providing results for both: Mass fraction (%) *versus* Temperature (°C), and dm/dt ($\% \cdot \text{min}^{-1}$) *versus* Temperature (°C). Furthermore, ignition and burnout temperatures also arise from TGA and DTG analysis. As representatives for a consistent combustion quality, those indexes show the following behavior: $S_{Index_W-01} > S_{Index_W-02} > S_{Index_NW-01}$; while for the ignition rate, $Di_{Index_W-02} > Di_{Index_W-01} > Di_{Index_NW-01}$. Those behaviors does not have, direct or indirect, relationship to the ones obtained for Q_{index} (Table 2); thus, indicating lack of consistency in pointing out a combustion index that applies to solid fuel samples as the ones available for biomass (sawdust, pellets and briquettes).

Table 3. Parameters for S_{Index} and $D_{Ignition}$ determination (Lu and Chen, 2015).

	W-01	W-02	NW-01
$(dm/dt)_{max}$	17.61	13.28	9.42
$(dm/dt)_{average}$	1.78	1.83	1.74
$T_{Ignition}$ [°C]	288	290	256
$T_{Burnout}$ [°C]	475	485	491
$t_{ig}(s)$	27.25	27.46	23.83
$t_p(s)$	42.21	31.17	28.96
$S_{Index} \cdot 10^7$ [$\%^2 \cdot (\text{min}^2 \cdot \text{C}^3)$]	7.92	5.94	5.097

D_{Ignition} · 10³ [%/min³]	15.31	15.51	13.65
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Table 4 indicates non-dimensional numbers, resulting from combinations of representative parameters for the solid fuel itself (commercial pellets) and the resulting combustion process. Considering a qualitative comparison, the following applies: a) Good agreement occurs between either, π_1 or π_2 or π_3 , and S_{Index} , i.e., $\pi_{1,3,4_{W-01}} > \pi_{1,3,4_{W-02}} > \pi_{1,3,4_{NW-01}}$, i.e., once $\pi_1 = f(\text{HHV}, R_{Time}, A)$, $\pi_3 = f(\text{TP}, R_{Time}, m)$, and $\pi_4 = f(C_p, T_{max}, R_{Time}, m)$, and those parameters have close consistency to TGA procedure under controlled atmosphere and adiabatic conditions; b) No agreement occurs for Q_{Index} and the four non-dimensional; c) No agreement occurs for π_2 and any combustion index, or non-dimensional numbers, and once $\pi_2 = f(\rho, m, A)$, probably pellets density (Table 1) were not significantly different to indicate a quality behavior or then, mass and grid area remaining almost the same for all test procedures in this work did not indicate a combustion quality improvement or worsening – indicating interesting possibilities in a broader range of future experiments.

Table 4. Non-dimensional numbers as combustion quality representation.

	W-01	W-02	NW-01
$\pi_1 \cdot 10^{14}$	6.232	5.583	3.202
π_2	42.243	48.858	39.047
$\pi_3 \cdot 10^{11}$	4.246	3.759	1.361
$\pi_4 \cdot 10^{17}$	3.388	3.200	1.269

4. CONCLUSIONS

Mains conclusions are: a) The combustion index based on the Quirino methodology showed no relation with the combustion index that is based on the TGA parameters; b) The combustion index based on the methodology using the TGA parameters for calculation showed a relationship with three of the Adimensionals proposed; c) The adimensionals that best represented the S_{Index} were $\pi_1 = f(\text{HHV}, R_{Time}, A)$, $\pi_3 = f(\text{TP}, R_{Time}, m)$, and $\pi_4 = f(C_p, T_{max}, R_{Time}, m)$, the adimensional $\pi_2 = f(\rho, m, A)$ Did not show any relationship with any of the two methodologies for calculating the combustion index.

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