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AN EXPERIMENTAL INVESTIGATION ON TORREFACTION OF BOCAÚVA (SHELL) AND EUCALYPTUS (SAWDUST)

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Abstract. *Global warming and the depletion of fossil fuels is a common concern in the actuality. An alternative that has being gaining interest is biomass, as waste to energy source. The biomass, primarily obtained from cultivated forest (as Eucalyptus), from industrial processing, from animal breeding, extractive harvesting activities (as Bocaúva), among others. Typically available at Mato Grosso do Sul state, where the Cerrado is a biome from Brazil´s Central-West region, Bocaiúva shell and Eucalyptus sawdust are residual biomass from extractive activities, charcoal production and paper and pulp industries. Torrefaction is a thermal process that can increase biomass HHV (kJ/kg), which results in a solid fuel with improved energy characteristics, for retaining most of its volatile matter and eliminating all of its humidity that results great differences in HHV and LHV (High and Low Heating Values, respectively). This paper aims to point out improvements energy characteristics when torrefaction is employed in residual biomasses. Results indicates Eucalyptus sawdust HHV increases from 15.73 kJ/kg (*in natura*) up to 19.00 kJ/kg (260 °C), while for Bocaúva shell HHV increases from 19.26 kJ/kg (*in natura*) up to 20.58 kJ/kg (260 °C), both for 60 minutes of residence time. These residual biomasses are typically found at the Cerrado (at Mato Grosso do Sul state), a biome from Brazil´s Central-West region.*

Keywords: *Residual biomass; Renewable energy; Combustion; Characterization; Thermal treatment;*

1. INTRODUCTION

A great challenge to the technological development and capitalist society is the greenhouse effect, caused by gases such as carbon dioxide (CO2) and methane (CH4), which are mostly released due to human's industrial activities. Those industries increasingly need energy from primary sources, as fuel for thermal power generation, as well as sources for electricity generation. Therefore, energy sources such as biomass have been researched, revealing themselves of a great importance as a full replacement alone or in combination with coal (co-firing) to generate heat or electricity in power plants. According to ANEEL (2015) electric energy matrix in Brazil has an installed capacity of 146,386 MW, where biomass accounted for 12,946 MW (8.84%) and coal for 3,614 MW (2.46%).

Torrefaction is a thermochemical treatment of biomass that occurs between 200 and 320°C. It is conducted at atmospheric conditions and in the absence of oxygen (Kaliyan, *et al*., 2014). This process has been considered as one of the most suitable pre-treatment processes for biomass, particularly for thermal conversions as pyrolysis, combustion, gasification and co-combustion system (Basu, *et al*., 2014). The torrefaction provides an intermediate product between dry biomass and coal. The main product is a solid material that retains 75-95% of the original energetic content (Prins, *et al*., 2006).

Torrefaction, which was presented in France in the 1980s (Doat, 1985) was researched as a biomass enhancement method of different characteristics, seeking an approach to the calorific value of coal for example. Most of the hemicellulose in biomass depolymerizes in the torrefaction process, releasing volatiles of low energy values, thus leaving the remaining solid with high energy density (Sarvaramini, *et al*., 2013)

When biomass is torrefied, there is an increase in concentration of volatile materials and a decrease of moisture content. Moreover, its hydrophobicity (ability to absorb water) is decreased, its grindability (crush resistance) and durability is increased, and thus its performance is improved. (Li, *et al*., 2012). As a consequence of these parameter improvements, the fuel High Heating Value, an important feature, is also increased. The higher the torrefaction temperature, the better the characteristics mentioned.

According to results of Basu, *et al*., (2014), the ideal roasting temperature, particle size and residence time that were evaluated by a model simulation were estimated to be around 290 °C, 24 mm and 10 h, respectively, under the conditions given. From results of Chen, *et al*., (2014), obtained from a torrefaction using a fixed bed, it was found that the torrefaction with rapid temperature elevation influenced the samples with a darkened color, improved grindability, increased carbon content and reduced oxygen content. In addition, temperature in the range of 260-290 °C is suggested as the best condition for biomass pyrolytic polygeneration.

According to Oliveira (2013), the torrefaction process takes place in five phases. The first is an initial heating to about 130 °C, in which the biomass loses moisture. The second consists in a post drying and an intermediate heating, in which the temperature is gradually increased to 200°C and physically bound water is released. The process really only occurs in the third phase where the temperature is around 200°C, although it varies depending of the biomass. During this period, there is a weight loss and destruction of hemicellulose. The destruction of the cellulose occurs between approximately 330-370°C in the fourth stage of the process. In the fifth and last phase, temperatures are over 350°C, and the formation of coal is present, which entails severe degradation of biomass.

At Brazil´s Central-West, primarily as a result of the big pulp production in industries in the city of Três Lagoas, Eucalyptus has a great highlight in pulp and paper industries, as well for charcoal production. Moreover, native species at the Brazilian Cerrado are abundant in the region, allow their treatment with torrefaction and a subsequent use in small power plants for firing or co-firing (with other biomasses, coal and other residues). Bocaiuva fruit is one of the possibilities, in which the shell is used as biomass and its pulp as food. As the Central-West region has great prominence in agricultural production, the waste of straw and bagasse, and the remaining of corn and sugarcane crops can mainly me used as solid fuels at power plants and burned directly in to the boilers in small or big industries.

All these biomasses are pointed out as potential biomass energy sources, therefore as potential solid biofuels for industrial burning (single fuel firing or combined, also known as co-firing or co-combustion), if a thermal pre-treatment as torrefaction is considered, for combustion performance improvements and LHV intensification.

2. METHODOLOGY

The procedure performed was torrefaction of the Eucalyptus sawdust and Bocaúva's shell. The process was considered for 3 (three) different reference temperatures. In the first, torrefaction occurs at 180±10 °C, the second at 220±10 °C and the third at 260±10 °C. For each reference temperature, 3 (three) different residence times were considered, namely 20, 40 and 60 minutes.

2.1 Torrefaction process

Materials used are presented in next figures. Figure 1 shows the equipment used for the biomass torrefaction. The material was first dried in a kiln (Sppencer scientific 420-1d), Fig 1(a). Then, torrefaction was conducted in a muffle furnace, Fig 1(b), with the aid of a metal cylinder, in which the samples were introduced, figure 1(c). Particle size reduction was accomplished using a Wiley mill (SOLAB Sl31), Fig 1(d). For samples storage, glass desiccators were used, Fig. 1(e). For weighing the samples, a Mark S3102- Precision Balance 3100g (0.01 g) was used, from Bell Engineering, Fig. 1(f).

Figure 1. Equipments used for torrefaction process.

Experimental procedure: 10 grams of eucalyptus wood with 0% of moisture (after fully drying, NBR 8118 (ABNT, 1996)) was crushed and introduced in the metal cylinder (Fig. 1c) and then in the furnace (Fig. 1b) previously heated with at the torrefaction temperature. After that, the furnace's door was closed and the cylinder with biomass remained inside the equipment for a established time (20, 40 or 60 minutes). After expiry of the residence time, the biomass sample was removed and then placed in a Petri plate and introduced into the glass desiccator until reaching ambient temperature. Following that, the set (plate and sample) were weighed and its image registered (see results section). Table 1 shows in summary the parameters considered to obtain results in this work.

Table 1. Temperature and time of residence of the samples

Samples	**Temperature**	**Residence time**
Eucalyptus wood; Bocauíva'shell	180±10°C	20 min; 40 min; 60 min
	220±10°C	
	260±10°C	

After the heating treatment (torrefaction), according to the experimental procedures describer in this work, samples were split in 1 g. Then, placing it in to the crucibles to proximate analysis (volatile matter and ash content, NBR 8118 (ABNT, 1996)). After seven days, an arbitrary chosen time for the sample to see if it absorbs back moisture, moisture content was again determined, all according to the methodology described in item 2.3 of this work.

2.2 Proximate Analysis

Procedures for proximate analysis results were performed according to NBR 8112 (ABNT, 1986). The moisture content test was conducted in a Sppencer scientific 420-1d stove as shown in figure 1(b). Ash and volatile matter analysis was conducted in a muffle furnace Novus N1100, Fig. 2. All samples were stored after the experiments in desiccators as shown in figure Fig. 1(d).

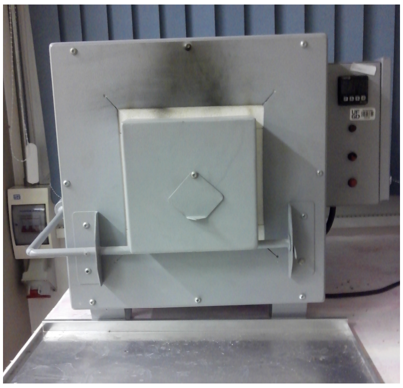


Figure 2. Muffle furnace – UFGD Energy Engineering facilities.

2.2.1 Moisture Content

To determine the moisture content (MC) in the samples, first we must take the empty crucibles to the greenhouse, where they will remain at 105±5 °C for 60 minutes. After the crucibles are dry, we insert 1g of the prepared sample. It is left in the greenhouse again during the total drying time determined for each biomass sample. Mass values at the process beginning and ending are measured, to allow the calculation of the moisture content according to Eq. (1).

MC represents moisture content in wet basis. MBS, *in natura* and MH2O represents, respectively, the mass of the biomass in natura and water mass contained in the sample.

$$MC = (MH20)/(MBS,in\ natura).100 \quad (1)$$

2.2.2 Volatile and Ash content

The volatile matter and ash content measurements, respectively, the percentage of biomass that volatilizes during combustion and the amount of ash remaining after the end of the combustion process.

For the volatile matter content measurement, 3 crucibles of each sample capped with 1 gram of biomass with 0% moisture were used. The samples were placed in an open door muffle furnace at 900±10 °C for 3 minutes and then inside it for another 7 minutes during which the furnace remained with the door closed. At the end of the period, the crucibles were placed in a desiccator to reach room temperature, to be posteriorly weighed.

For the ash content measurement, 3 crucibles were placed uncapped with the equivalent of 1 gram of biomass of each sample without moisture inside the oven for 1 hour at 700±10°C. Thereafter, the crucibles were placed again in the desiccator to reach room temperature, and weighed.

For the calculations of volatile matter content and ash content equations 3 and 4 were used, respectively.

$$VM\ (\%) = (M_{vm} / M_{bs,dried}).10 \tag{2}$$

$$AC\ (\%) = (M_{ash}/M_{bs,dried}).100 \tag{3}$$

M_{vm} represents mass of volatile matter, M_{ash} represents mass of ash and $M_{bs,\ dried}$ represents mass of the biomass after drying.

2.2.3 Fixed carbon content (FC)

$$FC\ (\%) = 100\text{-}(AC+VM) \tag{4}$$

2.3 High Heating Value (HHV)

High heating value was calculated based on proximate analysis experimental results, in accordance to a correlation given by Parikh (2005). Equation (5) shows the mathematical correlation for HHV.

$$HHV = 0.353.(FC) + 0.1559.(VM) - 0.0078.(AC) \tag{5}$$

HHV is the high heating value (kJ/kg). Unfortunately, HHV was not possible to be obtained by experimental as indicated by ABNT standards, once the heat pump at UFGD laboratory out of order. Then authors considered Eq. (5) as a good correlation available in the literature for HHV estimation. Although Eq. (5) is originally indicated for biomass *in natura*, authors understand it is valid for any biomass (torrefied or *in natura*), if its parameters are lies between the minimum and maximum limit values considered by Parikh (2005).

The correlation (Parikh, 2005) was obtained with ~40 biomass samples with different values for FC, VM and AC. FC content in these samples varies from 11.3 up to 33.9%, while VM content varies from 62.9 up to 88.2% and AC varies from 0.1 up to 17.2%. Then, as biomass samples after torrefaction in the present work have FC, VM and AC between these limit values, Eq. (5) is consistent and valid to the results herein obtained. Torrefaction process is able to increase the HHV (in fact the LHV), once moisture content will be eliminates as well as some VM content.

3. RESULTS AND DISCUSSION

3.1 Eucalyptus sawdust

Tables (2) and (3) are for Eucalyptus sawdust. Results presents are for *in natura* and torrified biomass. as performed. Before torrefaction starts, see Table (3), drying of *in natura* biomass is performed, thus Eucalyptus sawdust enters the process with 0% of moisture content (in other words, samples are not anymore *in natura*), see details in methodology section. Still in Table (3), results are for three different torrefaction temperatures and three different residence times.

Table 2. Proximate analysis and HHV - Eucalyptus *in natura.*

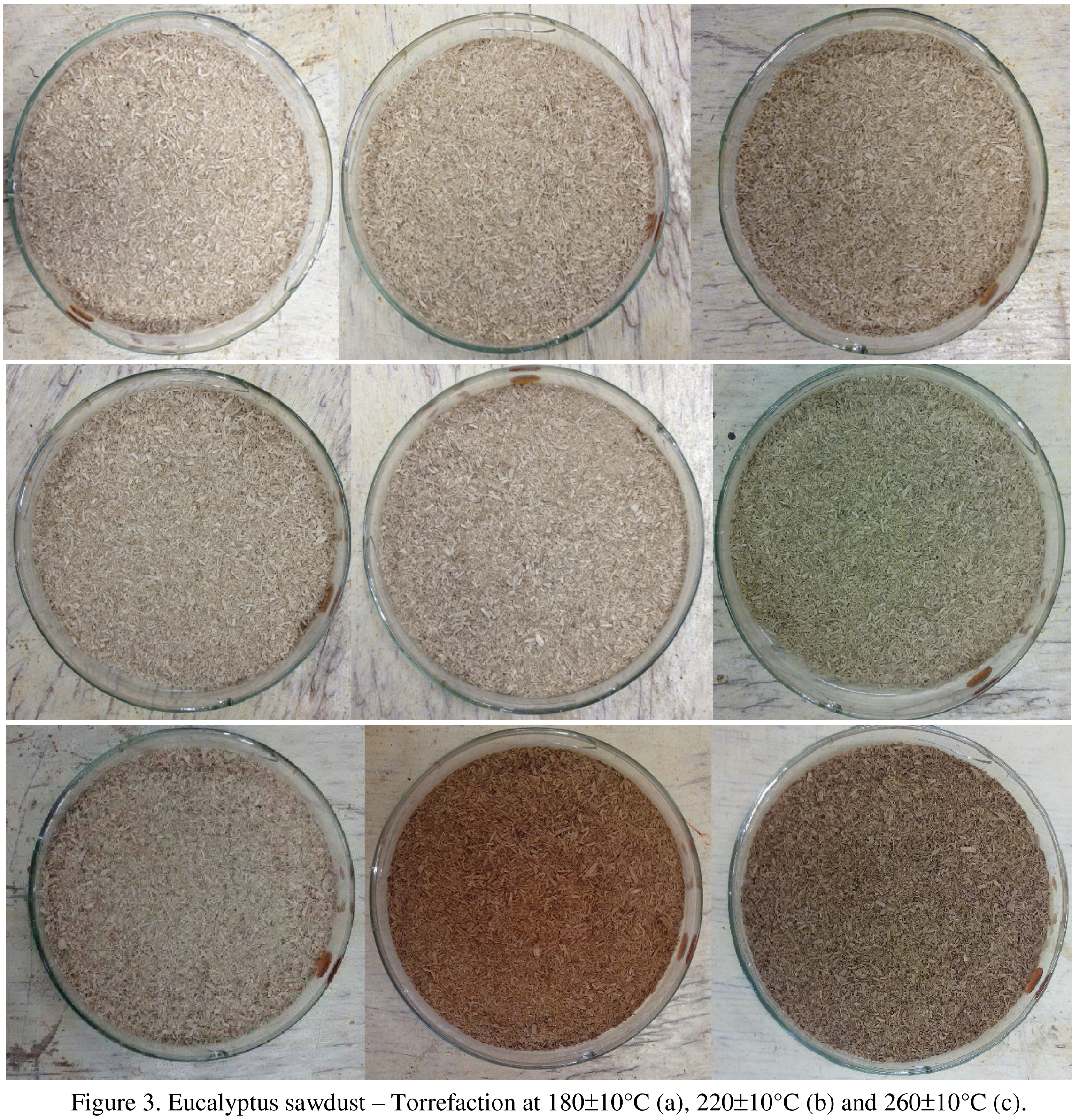
MC (%)	VM (%)	AC (%)	FC (%)	HHV (MJ/kg)
8.00	81.00	2.00	17.00	18.61

In the last column in Table (3), MC (moisture content) seven days after the torrefaction process (Eucalyptus sawdust). This is to evaluate its hygroscopicity, that is the ability to reabsorb humidity after some time, and these results show that the samples absorb lower and lower water as higher is the residence time. Still in Table (3), as long is the residence time, the lower are VM (low energy gases), while FC and HHV increases and AC oscillates. Biomass valorization occurs (energy and economic value) when increasing energy per mass unit (kJ/kg), that is, increased HHV after biomass torrefaction when compared to in natura biomass. Thus, torrefaction process implies in HHV improvements, except for one condition (220°C and 40 minutes, probably due to uncertainties inherent to the proximate analysis performed), reaching up to 3.2%, 3.3% and 5.2% increases, respectively for 180, 220°C and 260°C. Thus, indicating that increasing in time and in temperature implies in Eucalyptus sawdust valorization.

Table 3. Proximate analysis, HHV and MC (after 7 days) – dried Eucalyptus torrefied.

Residence time (minutes)	VM (%)	AC (%)	FC (%)	HHV (MJ/kg)	HHV increase (%)	MC, after 7 days (%)
	180±10°C					
20	81.00	1.00	18.00	18.97	1.9	8.0
40	80.50	0.90	18.60	19.11	2.7	7.5
60	80.00	0.90	19.10	19.21	3.2	6.5
	220±10°C					
20	82.50	1.00	16.50	18.68	0.4	8.5
40	81.06	3.70	15.24	17.99	-3.3	8.5
60	80.00	0.85	19.15	19.23	3.3	7.0
	260±10°C					
20	82.25	1.05	16.70	18.71	0.5	8.0
40	79.75	1.00	19.25	19.22	3.3	6.0
60	78.00	1.00	21.00	19.57	5.2	4.5

Figure 3 (a, b and c) shows the images for the three samples of Eucalyptus, subjected to torrefaction at 180±10°C, 220±10°C e 260±10°C, respectively. The samples residence time, from left to right are: 20, 40 and 60 minutes. These results indicate a tendency in the samples to have a darkened color, as increases the residence time and process temperature. As pointed out from Table (3), increases in these parameters, increases HHV and lowers hygroscopicity.



a)
b)
c)

Figure 3. Eucalyptus sawdust – Torrefaction at 180±10°C (a), 220±10°C (b) and 260±10°C (c).

3.2 Bocaiúva shell

Tables (4) and (5) are for Bocaiúva sawdust. As in Tables (2) and (3), these results are for three different torrefaction temperatures and three different residence times. Hygroscopicity results are similar to those for Eucalyptus sawdust, except for 260±10°C when MC does not lowers down as residence time increases.

Table 4. Proximate analysis and HHV - Bocaiúva *in natura.*[1]

MC (%)	VM (%)	AC (%)	FC (%)	HHV (MJ/kg)
7.40	74.92	3.51	21.36	19.19

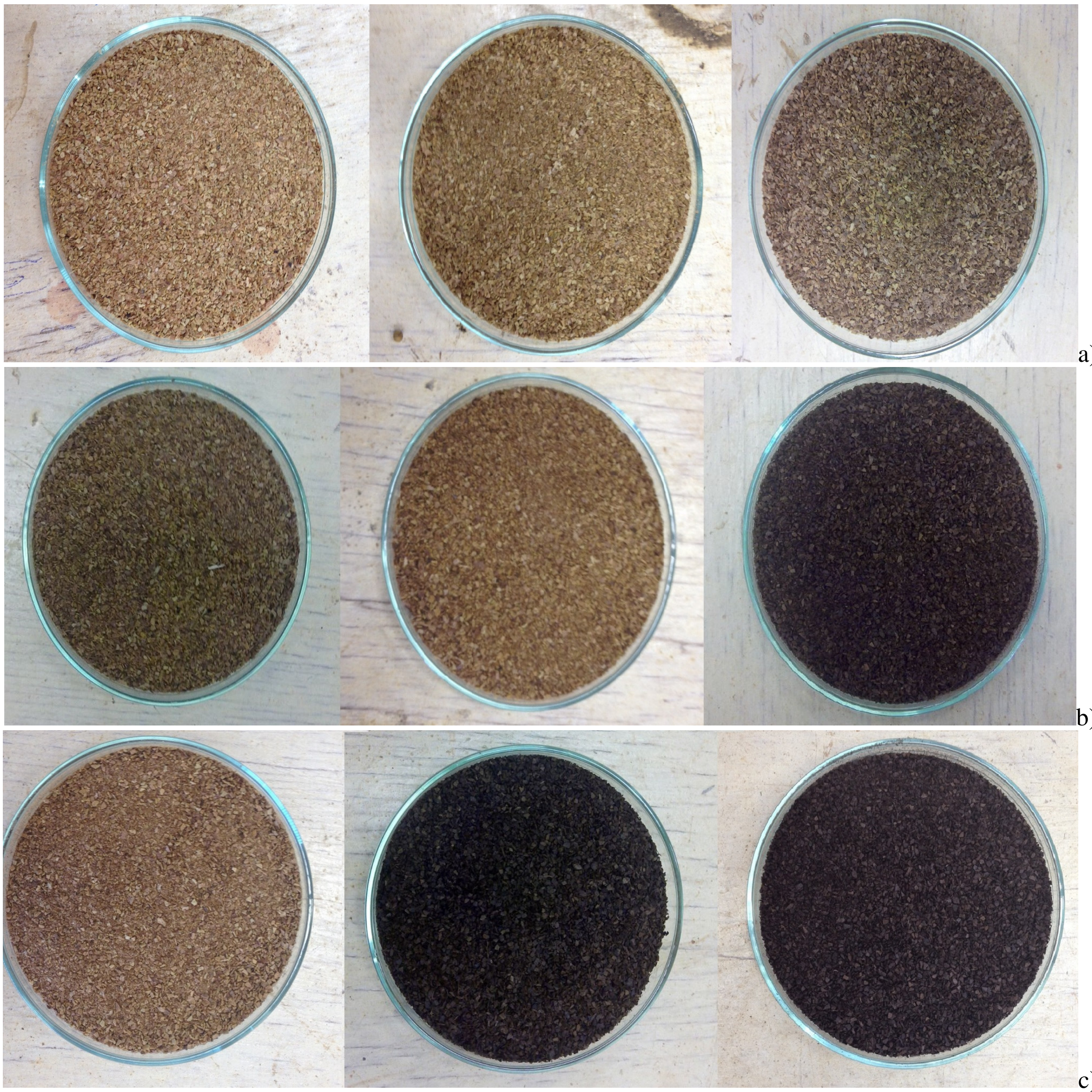
[1]Results according to Silva *et al* (2014).

Table 5. Proximate analysis, HHV and MC (after 7 days) – Dried Bocaiúva torrified.

Residence time (minutes)	VM (%)	AC (%)	FC (%)	HHV (MJ/kg)	HHV increase (%)	MC, after 7 days (%)
	180±10°C					
20	72.00	3.55	24.45	19.83	3.3	9.0
40	71.50	3.25	25.25	20.03	4.4	7.0
60	71.00	3.65	25.35	19.99	4.2	8.0
	220±10°C					
20	73.00	2.25	24.75	20.10	4.7	6.5
40	70.33	2.60	27.07	20.50	6.8	7.5
60	69.50	3.50	26.50	20.24	5.5	7.0
	260±10°C					
20	72.50	2.65	24.85	20.05	4.5	7.0
40	71.00	2.55	26.45	20.39	6.3	7.0
60	62.50	2.30	35.20	22.15	15.4	7.0

From Table (5), it is observed a similar behavior as in Table (3) for Eucalyptus sawdust, that is, as long is the residence time, the lower are VM (low energy gases), while FC and HHV increases and AC oscillates. Torrefaction process implies in HHV improvements for all conditions, but is remarkable to point out that 40 minutes is the higher residence time to reach higher HHV and HHV decreases when residence time is higher (see 60 minutes for all three reference temperatures). In other words, HHV reaches maximum values in 40 minutes of residence time for 180°C (4.4%) and 220°C (6.8%) and 60 minutes of residence time for 260°C (15.4%). Thus, indicating that, in general, increasing in residence time and temperatures implies in Bocaiuva shell valorization. As for hygroscopicity for the terrified Bocaiuva shell, results indicates lower and lower water absorption as high is the residence time, except for one case (180°C and 60 minutes).

Figure 4 (a, b and c) shows the images for the three samples of Bocaiúva, subjected to torrefaction at 180±10°C, 220±10°C e 260±10°C, respectively. The samples residence time, from left to right are: 20, 40 and 60 minutes. These results indicate analogous tendency as Eucalyptus to have a darkened color, increases HHV and lowers hygroscopicity.



a)

b)

c)

Figure 4. Bocaiúva shell – Torrefaction at 180±10°C (a), 220±10°C (b) and 260±10°C (c).

4. CONCLUSIONS

This paper presented a study on torrefaction process as thermal treatment to improve energy characteristics of residual biomasses from Brazil´s Central-West region (Mato Grosso do Sul state). Increases in HHV and decreases in hygroscopicity are able to provide biomass valorization for combustion processes and as solid fuel in the market. Future studies on cofiring (with coal and other residues) are also intended.

From results obtained, main highlights are pointed out next:

a) Eucalyptus sawdust torrefaction is able to increase HHV in 5.2%, from 18.61 kJ/kg (*in natura*) up to 19.57 kJ/kg (260±10°C, 60 minutes of residence time);

b) Bocaiúva shell torrefaction is able to increase HHV in 15.4%, from 19.19 kJ/kg (*in natura*) up to 22.15 kJ/kg (260±10°C, 60 minutes of residence time);

c) Hygroscopicity parameter is of great importance when considering biomass storage for a quite long time to the moment when it is going to be converted into thermal energy and/or electrical energy, in small-medium power plants;

d) As dark are the biomass colors, after torrefaction treatment, indicated good qualities for energy use purposes;

e) Experimental results for HHV to be obtained in future works will corroborate to results obtained by HHV correlations from literature considered in this work (see methodology section);

All results considered, authors conclude that torrefaction temperatures of 260°C (or even higher) and 60 minutes of residence time (or even higher) are indicated to improve energy valorization of these typical residual biomasses found in Brazil´s Central-West region. It is necessary to perform an energy balance to quantify the quantity of energy required for the torrefaction processes and the quantity of energy increases.

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5. REFERENCES

ABNT – Associação Brasileira de Normas Técnicas. 1996. "NBR 8112: Carvão Vegetal – Análise Imediata: método de ensaio.

ANEEL – Agência Nacional de Energia Elétrica, 2015. "Banco de Informações de Geração". 15 March, 2015. <http://www.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm>

Basu, P., *et al*, 2014. "An experimental and theoretical investigation on torrefaction of a large wet wood particle". *Bioresource Technology*. 159, 215–222.

Chen, Y., *et al*, 2014. "Torrefaction of agriculture straws and its application on biomass pyrolysis poly-generation". *Bioresource Technology*. 156, 70–77.

Doat J., 1985. "Un noveau produit énergétique pour les pays en dévelopment: le bois torréfié". *Revue Bois et Forêts des Tropiques,* 208(2e trimestre).

Kaliyan N., R. V., M., Tiffany D., G., Lee W., F., 2014. "Life cycle assessment of a corn stover torrefaction plant integrated with a corn ethanol plant and a coal fired power plant". *Biomass and bioenergy.* 63, 92-100.

Leal da Silva, R. *et al,* 2014. "Experimental results for proximate analysis and estimations for elemental composition and HHV: Bocaiúva (shell) and Crambe (bagasse) as residual biomass". In: *Proceedings of the VIII Congresso Nacional de Engenharia Mecânica - CONEM 2014.* Uberlândia-MG, Brazil. 8p.

Li, H., *et al*, 2012. "Torrefaction of sawdust in a fluidized bed reactor". *Bioresource Technology* 103, 453–458.

Parikh, J., Channiwala, S. A., Ghosal, G. K., 2005, "A correlation for calculating HHV from proximate analysis of solid fuels", *Fuel*, nº 84, p. 487-494.

Prins, M.J., K.J. Ptasinski, and F.J.J.G. Janssen. 2006. "Torrefaction of wood: Part 1: Weight loss kinetics". *Journal of Analytical and Applied Pyrolysis,* 77 (1).

Sarvaramini, A., Assima, G.P., Larachi, F., 2013. "Dry torrefaction of biomass –Torrefied products and torrefaction kinetics using the distributed activation energy model". *Chem. Eng*. J. 229, 498–507.

Oliveira, G. C. C., 2013. "Avaliação do ciclo de vida da produção de biomassa torrefada para a gaseificação". 78 p. University of Brasília.

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