

## ENCIT-2018-0345 EUCALYPTUS WOOD DRYING AT DIFFERENT TEMPERATURES AND ASPECT RATIOS

Tayná Matos de Moraes <sup>1</sup>  
Carolina Santana Michels <sup>2</sup>  
Robson Leal da Silva <sup>3</sup>  
Omar Seye <sup>4</sup>  
William Renzo Cortez Vega <sup>5</sup>  
Liomar de Oliveira Cachutê <sup>6</sup>  
Augusto Salomão Bornschlegell <sup>7</sup>  
Jaime Humberto Palacio Revello <sup>8</sup>

UFGD - Universidade Federal da Grande Dourados, Road MS-270 (Dourados-Itahum), km12, Zip Code: 79804-970, Dourados- MS  
[taynamoraes@gmail.com](mailto:taynamoraes@gmail.com)<sup>1</sup>, [csmpasqualli@gmail.com](mailto:csmpasqualli@gmail.com)<sup>2</sup>, [robsonsilva@ufgd.edu.br](mailto:robsonsilva@ufgd.edu.br)<sup>3</sup>, [omarseye@ufgd.edu.br](mailto:omarseye@ufgd.edu.br)<sup>4</sup>,  
[williamvega@ufgd.edu.br](mailto:williamvega@ufgd.edu.br)<sup>5</sup>, [liomarcachute@ufgd.edu.br](mailto:liomarcachute@ufgd.edu.br)<sup>6</sup>, [augustosalomao@ufgd.edu.br](mailto:augustosalomao@ufgd.edu.br)<sup>7</sup>, [jaimerevello@ufgd.edu.br](mailto:jaimerevello@ufgd.edu.br)<sup>8</sup>

**Abstract.** *Eucalyptus wood is the primary raw material in the industrial processing for the production of pulp, paper, and charcoal in Brazil, requiring a reduced moisture content. Usually, the drying occurs by natural convection heat transfer (outside on the ground), but using forced convection is an appealing possibility in industries, as the availability of residual thermal energy from a variety of processes, which provides hot airflow for drying. Thus, this study aims to analyze the behavior of moisture exit in eucalyptus billets, with different aspect ratios (L/D) submitted to forced drying between 100-200°C. Methodology considered small size billets (eucalyptus wood), with geometry for three different aspect ratios (1, 2, and 3) and five drying temperatures (100°C, 125°C, 150°C, 175°C, and 200°C), with total time of residence registered after reaching moisture content stability criteria, obtained by measuring the samples mass. Drying occurred in a recirculating kiln, with intervals of 30 minutes to record the intermediate total mass of each sample, and 10 minutes of preliminary natural cooling weighed in glass desiccator, for each of the test temperatures. Additionally, the moisture content via proximate analysis (dust/sawdust wood) was obtained for comparison and benchmarking of the drying stabilization criterion, reaching 7.8-8.1%. Next, highlights from results: a) At 100°C free water removal occurs, while bound water is removed at higher temperatures; b) Water removal (free and bound) reaches higher values than moisture content from the proximate analysis (~8%); c) Drying time is lower as high the temperature, while higher weight loss occurs for longer residence times, consistent with heat and mass transfer theory; d) Aspect ratios under evaluation (AR~1-3) show small differences, reaching the same level of weight loss after 2-3h tests. Thus, a similar behavior may happen for real scale eucalyptus wood in charcoal production (AR~20).*

**Keywords:** *drying rate, diffusivity, pretreatment, thermal process, siderurgy.*

### 1. INTRODUÇÃO

Wood drying (*in natura*) aims to reduce the moisture content, that is, the amount of free water and hygroscopic material present. Regarding the wood carbonization process, as reduced is the moisture content, the lower will be the amount of energy required to obtain charcoal, once wood water evaporation involves enthalpy increase. Eucalyptus wood is the primary raw material in the industrial processing for the production of pulp, paper and charcoal in Brazil, requiring a reduced moisture content. Usually, the wood drying for charcoal production occurs by natural convection heat transfer, storage in outdoors areas with logs on the ground (Zanuncio et al., 2014). Nevertheless, drying by forced convection is an appealing possibility in industries, as the availability of residual thermal energy from a variety of processes, which provides hot airflow for drying.

In the furniture industry that requires compressing of wood, for example, the drying of the wood is the operation that consumes the higher energy amount (Zhao et al., 2015). In applications for energy purposes or solid biofuel obtaining (charcoal), the main advantage of the preliminary wood drying (thermal pretreatment) is increasing the process efficiency; pyrolysis (carbonization ovens) or combustion (boilers and furnaces); because it reduces the amount of energy required in the thermal process. On slow pyrolysis (or carbonization), drying occurs in the early part of the process as a whole, is required an exothermic step occurs, i.e., part of the wood combustion, resulting in carbon

conversion and other wood components in thermal energy, which is the heat required to evaporate water from wood, namely, removal of moisture. So, with the preliminary drying to pyrolysis or combustion, part of the eucalyptus which would be consumed, becomes charcoal, increasing the gravimetric yield (Valencia, 2003).

Additionally, there are qualitative gains from an environmental point of view, because the pre-drying assists in reducing levels of pollutants typically emitted in carbonization processes, such as respirable particles, carbon monoxide, and sulfur oxides, which are health risks, i.e., contribute to reducing emissions of greenhouse gases (Mandal et al., 2014).

Eucalyptus wood is a kind that has much higher drying time compared to other species (Valencia, 2003; Vermaas, 1995) because it does not have a drying step constant that is faster and more fluid. In this step, the water contained in the first layers of the wood evaporates by convection, as a combination of room temperature, air flow velocity, and relative humidity. That highlights its impermeability and the need for a more strict process than merely drying the natural drying of eucalyptus (Jankowskyc et al., 2000).

When originated from energy forests, eucalyptus wood is widely used for charcoal production in Brazil (MME, 2006; Uhlig, Goldemberg, and Coelho, 2008). The primary use is in the metallurgical sector, for the chemical reaction process of reduction to obtain pig iron and later "green" steel. In your natural form, iron ore is associated with oxygen, which must be removed, in the process of reduction; the carbon present in charcoal binds to oxygen in the pig iron to form CO and CO<sub>2</sub> (gas-phase), and is also used as an alloying element of mild steel (Fe-C) (Aguilar, 2005).

The world steel industry, spanning the carbon source used is coal, so charcoal produced from energy forest enters as a sustainable alternative. In Brazil, the steel industry consumes of 25-30% of the national production of charcoal (CGEE, 2010), an average of 6.9 million tons per year between 2000-10, resulting in average about 9.5 million tons of pig iron. In this sector, Brazil has highlighted by your international production of pig iron and carbon steel without the use of fossil carbon (coal). Minas Gerais state, in Brazil's Southeast region, concentrates the highest amount of steel mills in the country (Grossi, 2013; IBGE, 2013). The charcoal production originated from forestry in 2012 was 4 million tons, 23.5% higher than in 2011, accounting for 85% of the national output (Baptista, 2014).

From the preceding, there is a national industry challenge to promote more efficient carbonization and search for reducing pollutants emissions resulting from the charcoal process. Therefore, this paper seeks to contribute information for future improvement of the production of charcoal. Thus, this study aims to analyze the behavior of moisture exit in eucalyptus billets, with different aspect ratios (L/D) submitted to forced drying between 100-200°C. In here, it will be evaluated as parameters of the drying process, the temperature and geometry (billets), and the influence on the behavior of the drying process. The aim is to examine the possibilities of forced drying, identifying the best conditions that can result in higher energy efficiency and gravimetric yield. In here, parameters evaluations in the drying process are to be temperature, wood billets geometry, and its influence on the drying process behavior. The aim is to examine the possibilities of forced convection drying, identifying the best conditions that can result in higher energy efficiency and gravimetric yield when considering industrial scale process.

## 2. METHODOLOGY

### 2.1 Wood billets – samples and drying

Eucalyptus wood billets were obtained from commercial products, with variations in its nominal diameters and similar length, see Fig. 1. Cutting along wood billets axis was required to obtain increasing aspect ratios (AR). Additionally, for proximate analysis purposes, a knife mill provided size reduction to dust/sawdust.



Figure 1. Commercial wood package (5 kg), and Eucalyptus farm forest (source: [agrobrasil.tv.com.br](http://agrobrasil.tv.com.br))

Thus, drying procedure considered the small size billets (eucalyptus wood), with geometry for three different aspect ratios (AR = 1, 2, and 3) and five drying temperatures (100°C 125°C, 150°C, 175°C, and 200°C). Drying occurred in a

recirculating kiln, with intervals of 30 minutes to record the intermediate total mass of each sample. There was a 10 minutes time waiting, in a glass desiccators, for ambient cooling before using weighing on a digital scale.

Time for drying was registered after reaching moisture content stability criteria obtained by samples weigh measurements. Authors considered moisture content variations below 0.25% ( $\Delta M_{MC-water} \leq 0.25\%$ ) as a reference for drying time and test end. Each test temperature was accomplished in the same day (~480 minutes), with an exception for a couple of results obtained in two days test with no significant differences other than small hygroscopic effects (see discussions in results section).

Table 1 indicates reference parameters for drying test, L is for length (mm) and D is for diameter (mm). There are some variations on aspect ratio, but its range from 1 up to 3 remains as a general characteristic. Figure 2 shows the 15 wood billets after tests.

Table 1. for drying tests temperatures and geometry (mean parameters range for 15 wood billets).

Temperature (°C)	Aspect Ratio (AR = L / D)	L (mm)	D (mm)
100	~ 1	~ 60-100	~ 65-106
125			
150	~ 2	~ 110-150	~ 55-74
175			
200	~ 3	~ 150-220	~ 55-75



Figura 2. Eucalyptus billets for different AR (15 samples): ~ 1; ~ 2; ~ 3.

## 2.2 Proximate analysis – experimental procedure

Proximate analysis is obtained experimentally, in duplicate according to NBR 8112 (ABNT, 1986), and provides contents for: moisture in wet and dry basis ( $T_{MC,wb}$  and  $T_{MC,db}$ ;  $\Delta T_{MC} \leq 5\%$ ; particle size < 19mm), volatile matter ( $T_{VM}$ ;  $\Delta T_{VM} \leq 2\%$ ; 0,150mm < particle size < 0,210mm), ashes ( $T_{Ash}$ ;  $\Delta T_{Ash} \leq 10\%$ ; particle size < 0,210mm) and fixed carbon ( $T_{FC}$ ). That last one is calculated by difference, Eq. (4). Samples preparation recommendations were adapted to NBR 7402 and NBR 6922 (ABNT, 1981; 1982).

$$T_{MC,wb} (\%) = [ (M_0 - M_1) \cdot (M_0)^{-1} ] \cdot 100 \quad (1)$$

$$T_{MC,db} (\%) = [ (M_0 - M_1) \cdot (M_1)^{-1} ] \cdot 100 \quad (2)$$

$$T_{VM,db} (\%) = [ (M_2 - M_3) \cdot (M_1)^{-1} ] \cdot 100 \quad (3)$$

$$T_{Ash,db} (\%) = [ (M_4 - M_5) \cdot (M_1)^{-1} ] \cdot 100 \quad (4)$$

$$T_{FC,db} (\%) = (100 - T_{MC,db} - T_{VM,db} - T_{Ash,db}) \quad (5)$$

Where:

$M_0$  = Total mass before drying, g

$M_1$  = Total mass after drying (at  $105^\circ\text{C} \pm 5^\circ\text{C}$ ), g

$M_2$  = Total mass before volatile matter removal, g

$M_3$  = Total mass after volatile matter removal (at  $900^\circ\text{C} \pm 10^\circ\text{C}$ ), g

$M_4$  = Total mass after fixed carbon removal (at  $700^\circ\text{C} \pm 10^\circ\text{C}$ ), g

$M_5$  = Crucible mass without sample inside, g

Initially, the biomass sample should be long enough drying in the recirculation kiln until there are no changes in the mass recorded by the weigh device (digital scale). That is required to determine the drying time for each sample type

under analysis. Assessment with time intervals of 30 minutes for drying of the sample was performed, to identify the minimum time required for water removal, i.e., its moisture content. Total mass refers to crucible ( $V \approx 25\text{cm}^3$ ,  $D \approx 32\text{mm}$ ,  $h \approx 36\text{mm}$ ) plus biomass (dust/sawdust,  $\pm 1\text{g}$ ), according to NBR 8112 (ABNT, 1986), initially for charcoal analysis. A recirculation kiln was used for drying the wood billets.

Figure 3 shows equipment and devices for tests at UFGD facilities. From left to right, there are: Drying kiln (Spencer scientific, model 420-1d); knife mill (SOLAB, model SL31), for particle size reduction; Digital scale (Bell Engineering, Mark S3102 - Precision Balance 3100g, 0.01 g resolution) for weighing; Glass desiccator, for samples storage and cooling.

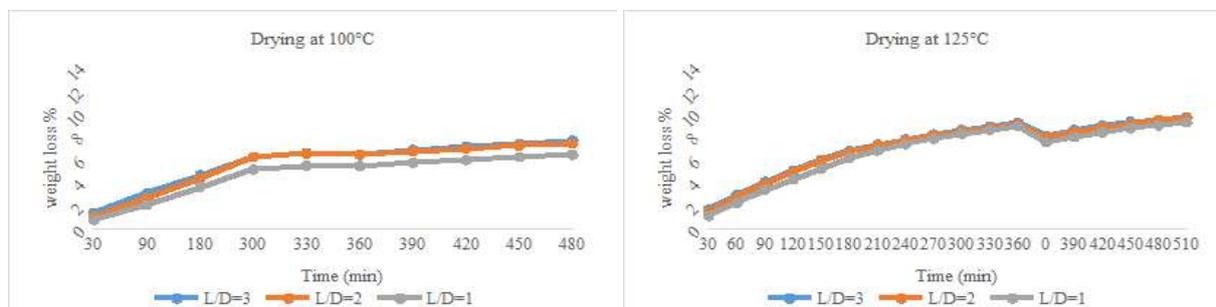


Figure 3. Equipment used for measurements and test procedure.

### 3. RESULTS AND DISCUSSION

Figure 4 presents drying behavior for wood billets submitted to temperatures from  $100^\circ\text{C}$  up to  $175^\circ\text{C}$ . Weight loss identifies the moisture content, which is 6.4-7.7% at  $100^\circ\text{C}$  after 480 minutes. Those values are consistent to proximate analysis for eucalyptus dust/sawdust samples, with the following results:  $T_{\text{MC,db}} = 7.8\text{-}8.1\%$ ;  $T_{\text{VM,db}} = 86.7\%$ ;  $T_{\text{FC,db}} = 12.6\text{-}13.1\%$ , and  $T_{\text{Ash,db}} = 0.4\text{-}0.6\%$ . Those parameters are consistent to other literature results: 82.1%, 17.6%, and 0.3% (Nones et al., 2015); 86.8%, 13.0%, and 0.16% (Silva et al., 2017a); 81.4%, 17.82%, and 0.79% (Cortez, Lora and Gómez, 2008); respectively for  $T_{\text{VM,db}}$ ,  $T_{\text{FC,db}}$ , and  $T_{\text{Ash,db}}$ .

Comparing to higher drying temperatures, the same order of magnitude for moisture content occurs at shorter times: 240 minutes ( $\sim 7.8\%$ ), 210 minutes ( $\sim 7.7\%$ ), 150 minutes ( $\sim 7.8\%$ ), respectively at  $125^\circ\text{C}$ ,  $150^\circ\text{C}$ , and  $175^\circ\text{C}$ . Thus, drying time is lower as high the temperature, consistent with heat transfer theory (Incropera, 2014). As test continues at those temperatures range, weight loss increases indicating that water removal still occurs, in this case, the ones inside wood cells (bound water), once free water is removed by evaporation at  $\sim 100^\circ\text{C}$ , i.e., proximate analysis. Then, assuming that only free water was removed at those drying temperatures (Gezici-Koç et al., 2017), mean values for moisture content when reaching  $\Delta M_{\text{MC=water}} \leq 0.25\%$  is the following: 510 minutes ( $\sim 9.5\%$ ), 450 minutes ( $\sim 10.3\%$ ), 300 minutes ( $\sim 10.5\%$ ), respectively at  $125^\circ\text{C}$ ,  $150^\circ\text{C}$ , and  $175^\circ\text{C}$ .



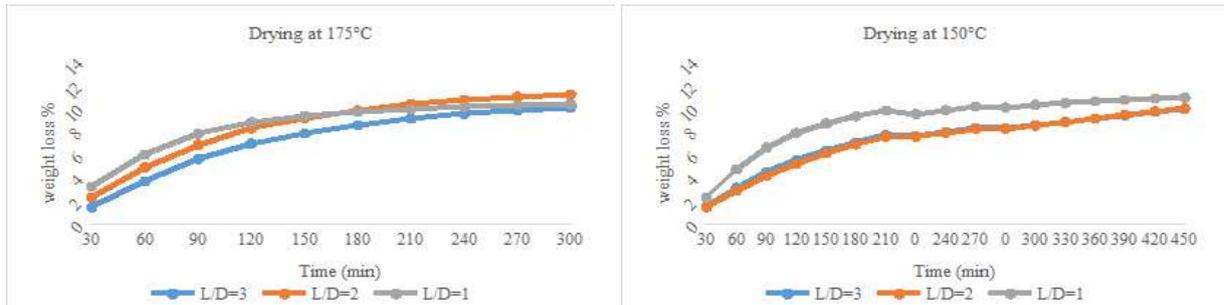


Figure 4. Weigh loss at 100°C, 125°C, 150°C, and 175°C.

At 200°C drying (Fig. 6, left), there is a possibility that substances other than water (free or bound) begins to exit from wood billets. Nevertheless, considering moisture content mean values for three AR, that condition requires 60 minutes to ~8.0% and reaches a maximum of ~14.7% after 480 minutes, when criteria for test end occurs. Figure 6 (right), compares all five drying temperatures; At 100°C, weight loss registers are missing for 60, 120, 150, 210, 240 and 270 minutes. When drying temperature increases, the mass transfer outside the wood also increases, also consistent with mass and heat transfer theory (Incropera, 2014).

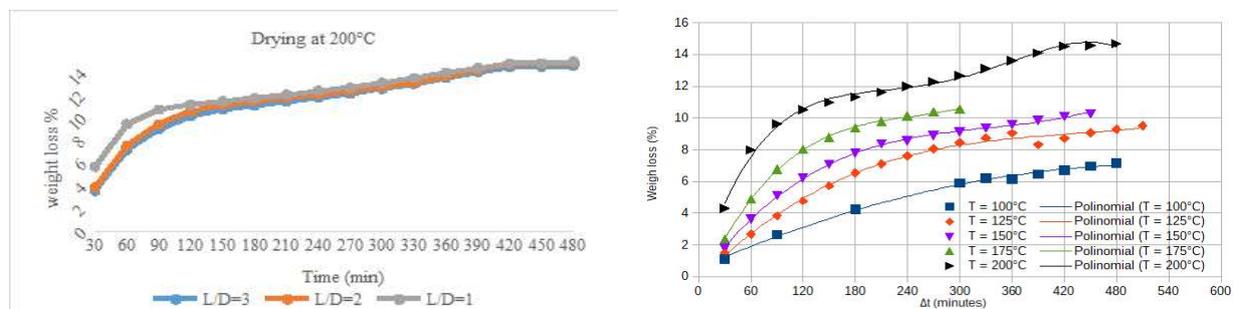


Figure 6. Weigh loss at 200°C and comparison for all test temperatures.

During tests in general, drying behavior for the three different aspect ratios shows small differences. As a whole, for ~8% moisture content obtained in proximate analysis and attending for test end criteria, the following applies to wood billets samples: a) two of them took 480 minutes at 100°C, 210 minutes at 150°C, and 60 minutes at 200°C; b) all three took 240 minutes at 125°C; c) at 175°C, one sample took 90 minutes, a second one took 90-120 minutes and the third one took 150 min.

Authors suggest that higher aspect ratios should be under tests (ex: AR~5-10, in future experiments, to evaluate its drying behavior for wood billets close to real applications in charcoal production ( $L \sim 3\text{m}$ ;  $D \sim 0.15\text{m}$ ;  $AR \sim 20$ ). Nevertheless, as results discussion in the present paper, differences for experimental  $AR = 1, 2$  and  $3$  are more prominent at the first 2-3h, and it tends to reach same moisture content levels for higher drying time in forced convection heat transfer. Then, similar behavior is expected to occur at higher AR. Drying rate ( $\text{g}\cdot\text{h}^{-1}$ ) is also suggested to be evaluated and compared to other literature results (Santos et al., 2003), as well as, drying kinetics as a function of wood thermodynamic properties (Silva et al., 2017b). Another possibility is to develop and validate mathematical models for wood drying, evaluating the effective diffusivity and temperature influences (Ferreira et al., 2012).

Experimental results point out that moisture content removal (free and bound water), from eucalyptus wood-billets, in the range of ~8-15%. For industrial purposes, it is necessary to quantify the availability of residual thermal energy (residual heat) from a variety of processes, which provides hot airflow for drying, or the required drying level for wood final use purposes (~30-35% moisture content in natural drying for carbonization).

#### 4. CONCLUSIONS

Main conclusions are:

- At 100°C, typically only free water removal occurs, while bound water is removed at higher temperatures, with volatile matter removal usually  $>180^\circ\text{C}$ , when the torrefaction process begins (usually up to  $300^\circ\text{C}$ );
- Water removal (free and bound) reaches higher values than moisture content from the proximate analysis (~8%), when drying by forced convection heat transfer, mainly at  $100\text{-}175^\circ\text{C}$  range, for a minimum residence time;
- Drying time is lower as high the temperature, for a specific weight loss value, while higher weight loss occurs for longer residence times, both consistent with heat and mass transfer theory;

d) Aspect ratios under evaluation (AR~1-3) show small differences, reaching the level of weight loss after 2-3h tests. Thus, a similar behavior may happen for real scale eucalyptus wood in charcoal production (AR~20).

## 5. ACKNOWLEDGEMENTS

R&D Project ANEEL/GERDAU “Desenvolvimento de sistema queimador de gás pobre com aplicação em caldeira de centrais termoelétricas”, through FUNCAMP/Unicamp and FUNAEP/UFMG. To scholarships for undergraduate engineering students from IC/ITI - Scientific Initiation and Industrial Technology Initiation, granted by and CNPq - National Council for Scientific and Technological Development. Also to UFGD/Energy Engineering facilities and technicians support.

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