EFFECTS OF TORREFACTION ON ENERGY PROPERTIES OF *Eucalyptus grandis* WOOD

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ABSTRACT: Torrefaction is a thermal treatment that promotes homogenization and improvement of energy properties of biomass. This study aims to evaluate the effects of torrefaction on the main energy properties of *Eucalyptus grandis* wood. Wood was torrefied at three distinct temperatures (220°C, 250°C and 280°C) and analyzed for gravimetric yield (ratio of dry wood mass to torrefied wood mass), bulk density (ratio of dry torrefied mass to dry torrefied volume), heating value (higher – HHV, lower – LHV and useful – UHV), energy density (ratio of heating value to bulk density) and energy yield (product of gravimetric yield and ratio of HHV of torrefied wood to HHV of feedstock). The obtained results revealed significant differences for all properties being analyzed except for bulk density, which showed no statistical difference between the control and the treatment at 220°C. Temperature 250°C generated the best energy density as a function of the increase in heating value and the slight decrease in bulk density.

Key words: Thermal treatment, energy density, heating value.

EFEITOS DA TORREFAÇÃO NAS PROPRIEDADES ENERGÉTICAS DA MADEIRA DE *Eucalyptus grandis*

RESUMO: *A Torrefação é um tratamento térmico que promove a homogeneização e o incremento das propriedades energéticas da biomassa. Nesta pesquisa, objetivou-se avaliar os efeitos da torrefação nas principais propriedades energéticas da madeira de Eucalyptus grandis. A madeira foi torrificada em três temperaturas (220°C, 250°C e 280°C) e, posteriormente, foi analisada quanto ao rendimento gravimétrico (razão entre a massa seca de madeira e a massa de madeira torrificada), à densidade aparente (razão entre a massa seca e torrificada e o volume seco e torrificado das amostras), ao poder calorífico (superior – PCS, inferior – PCI e útil - PCU), a densidade energética (razão entre o poder calorífico e a densidade aparente) e o rendimento energético (produto do rendimento gravimétrico pela razão entre o PCS da madeira torrificada e o PCS da madeira natural). Os resultados obtidos indicaram que houve diferenças significativas para todas as propriedades analisadas, com exceção da densidade aparente que não apresentou diferença estatística entre a testemunha e a temperatura de 220°C. A temperatura de 250°C gerou a melhor densidade energética em função do aumento do poder calorífico e da baixa queda na densidade aparente.*

Palavras-chave: Tratamento térmico, densidade energética, poder calorífico.

1 INTRODUCTION

Thermal treatment applied to wood causes chemical, physical and mechanical changes according to the increase in temperature. Thus a thermal treatment varies from the drying stage (elimination of free water) to the gasification stage (gas production), and in the gradient between these two extremes several substances are eliminated and formed following simple and complex reactions. The result is energy densification as a function of the higher carbon content in the remaining mass.

In thermal treatments the temperature gradient has a threshold between endothermic and exothermic processes. The last stage of endothermic conversion is torrefaction, which occurs at up to 280°C, at which point the exothermic phase begins and charcoal is formed (ANTAL JUNIOR et al. 2003). The torrefaction process occurs at relatively low temperatures (225 – 300°C) intended to produce a higher energy density fuel through hemicelluloses decomposition (PRINS et al. 2006). In the aggregate, wood begins to undergo thermal degradation (structural change plus water loss) at 180°C, with release of carbon dioxide, acetic acid and some phenolic compounds (GIRARD & SHAH 1991). Out of its three main components the first to degrade are hemicelluloses, starting at 225°C and being completely degraded at 325°C (ROWELL et al. 2005).

Studies on effects of thermal treatment on the physicochemical properties of wood demonstrated that the heating process prompts degradation of hydrophilic polysaccharides (hemicelluloses), reducing hydroxyl radicals where water molecules would otherwise usually bind (HAKKOU et al. 2006, MBURU et al. 2007). They also describe a relative increase in lignin content in relation to the initial mass, increasing the hydrophobic character of the material.

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In typical torrefaction process 70% of the dry mass is retained as a solid product containing 90% of the original energy content. The other 30% is converted into torrefaction gases containing only 10% of the energy content of the biomass (BERGMAN et al. 2005). Doat (1985) observed an average gravimetric yield of 75% in the torrefaction process, with 55-60% of carbon, 5-5.5% of hydrogen, 0.1-0.2% of nitrogen and 35-38% of oxygen in the elementary composition, with a heating value of 22-25 MJ/kg. The heating value of torrefied wood is in between that of anhydrous wood (18 MJ/kg) and charcoal (28 MJ/kg). Torrefied wood retains 70-90% of the initial feedstock mass while decreasing the volatiles content from 80% to 60-75% and the moisture content from 10% to 0-3% (PRINS et al. 2006).

This work aims to evaluate the effects of torrefaction on the energy properties of *Eucalyptus grandis* wood, including gravimetric yield, bulk density, heating value (higher and useful), energy density and energy yield.

2 MATERIAL AND METHODS

2.1 Preparation of test samples

This study consisted of torrefaction of *Eucalyptus grandis* wood as obtained from a tree stand of the experimental station of the Department of Forest Sciences of ESALQ/USP, in the municipality of Piracicaba, with trees aged 31 years. Three trees were felled and planks were cut to make test samples each with 2x4x8 centimeters. This chip size provides a more even transfer of heat inside the test samples, the transfer being more effective if done longitudinally as opposed to radially, and if done radially as opposed to tangentially (KOLLMANN 1984). Once torrefied, the test samples were submitted to analysis for determination of energy properties.

2.2 Torrefaction

The torrefaction system consisted primarily of a controlled temperature reactor, a precision scale accurate to 10^{-4} grams, a gas analyzer to determine contents of oxygen as well as carbon monoxide and dioxide and to prevent combustion, a converter between computer and other components, a control panel, a nitrogen source to secure an inert atmosphere inside the reactor, and a computer for data collection and processing (Figure 1).

Five test samples were torrefied in each trial run, one coupled to the precision scale for monitoring of mass loss, another with a thermocouple (thermocouple 1) resting on its tangential surface for monitoring of surface temperature, and another with a thermocouple (thermocouple 2) inserted through its tangential side halfway across the width (2 cm) for monitoring of inside temperature.

Table 1 summarizes the dynamics of torrefaction trial runs, including temperature, maximum rate of oxygen to secure an inert atmosphere, heating rate, minimum drying

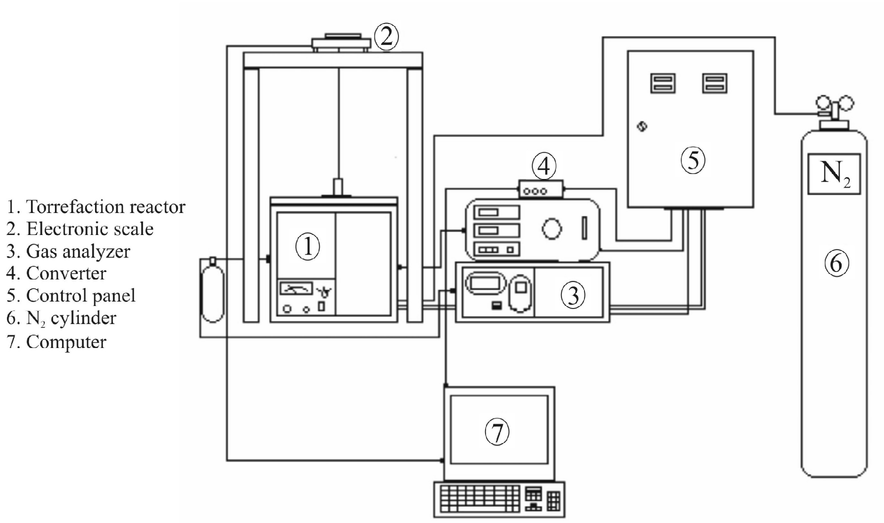


Figure 1 – Representation of the torrefaction system.

Figura 1 – *Esquema do sistema de torrefação.*

Table 1 – Illustrative table of torrefaction tests.

***Tabela 1** – Quadro ilustrativo dos ensaios de torrefação.*

Species	Treatments	Rate of O_2	Heating rate	Drying	Torrefaction set point interval
Eucalyptus grandis	T1 – control T2 – 220°C T3 – 250°C T4 – 280°C	≤ 5%	3°C/minute	~17 hours	60 minutes

time in a forced air circulation oven to obtain anhydrous wood (0% moisture), and torrefaction set point or time interval samples are kept at the final temperature.

The specific mass (*Sm*), in this case the bulk density (*BD*), was determined in agreement with COPANT 461 standard (COPANT 1972) by the ratio of mass to volume of wood, according to moisture content. Here, bulk density was calculated on the basis of 15% moisture content for the control sample and 0% moisture content for all torrefied samples. The volume of torrefied samples and feedstock samples was determined using a digital caliper.

The higher heating value (HHV) was determined on the basis of thermal energy generated by complete combustion of the sample inside a constant pressure chamber. A PARR 1261 bomb calorimeter was used in agreement with NBR 8633/84 standard (ABNT 1984). The lower heating value (LHV) subtracts the amount of energy required for condensation of water formed in complete combustion, being calculated by the following formula:

$$LHV = HHV - 1.36 \quad (1)$$

The LHV is then used to calculate useful heating value (UHV), which expresses the amount of energy per unit of mass, based on 15% moisture content for the control only. The basis for torrefied samples was 0% moisture content, the UHV being equal to the LHV in this case. The UHV was calculated by the following formula:

$$UHV = LHV*(1 - M.C.) - 2.51*M.C. \quad (2)$$

where M.C. is moisture content of wood on dry basis.

Energy density is a measure of the potential that a given volume of biomass has for generating energy. This concept relates the bulk density to the heating value of the fuel, providing the energy amount, in calories or joules, which are present in one (1) cubic meter of fuel (MJ/m³). Energy yield ($ç_e$) relates the mass yield to the higher heating value of wood and is calculated by the formula proposed by Bergman et al. (2005):

$$\eta_e = \eta_m \left(\frac{PCS_{torr}}{PCS_{nat}} \right) \quad (3)$$

Gravimetric yield (η_m) is the ratio of torrefied wood mass (M_{torr}) to initial feedstock mass (M_{nat}), dry at 0%.

$$\eta_m = \left(\frac{M_{torr}}{M_{nat}} \right) *100 \quad (4)$$

3 RESULTS AND DISCUSSION

Table 2 presents results of gravimetric yield, mean of five torrefied test samples per treatment. This variable indicates how much wood mass was lost after torrefaction. The low values of coefficient of variation (C.V.) demonstrate the similarity between all thermal treatments and the efficiency of the torrefaction system.

During treatments, different patterns were observed regarding final temperatures. In treatment 2, the thermocouples that measured temperatures on the surface (thermocouple 1) and through the inside (thermocouple 2) of the sample read values below the set point of 220°C (regulation thermocouple), namely 214.7°C on the surface and 215.4°C through the inside at maximum (Figure 2a).

In treatments 3 and 4, thermocouples inserted through the test samples read values above the respective programmed set points, with peaks of 253.4°C and 286.5°C, staying a few minutes until stabilization below the predefined temperatures. These peaks in treatments 3 and 4 express exothermic reactions that occur below the surface of wood subjected to heating.

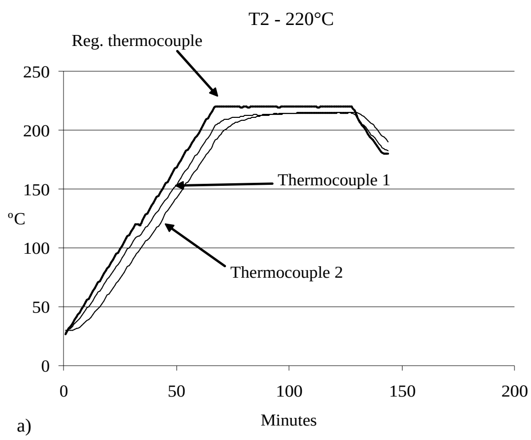
Similar reactions were observed in torrefaction procedures by Almeida (2007) and Inari et al. (2007). Rousset et al. (2004) pointed to the influence of sample thickness in occurrence of exothermic reactions, since the thicker the sample the more difficult it is for gases to exit, and this increases pressure and consequently temperature. Temperature peaks and loss of mass in treatments 3 and 4 are illustrated in Figures 3 and 4.

The decrease in density is closely related to loss of mass, especially hemicelluloses, being little influenced by volumetric changes, which are minor. Table 3 depicts the effects of torrefaction on bulk density.

Table 2 – Gravimetric yield of three torrefaction procedures.

***Tabela 2** – Rendimento gravimétrico das três torrefações.*

Treatment	Gravimetric yield (%)	C.V. (%)
T2 – 220°C	96.39	0.66
T3 – 250°C	88.27	0.91
T4 – 280°C	80.15	1.53



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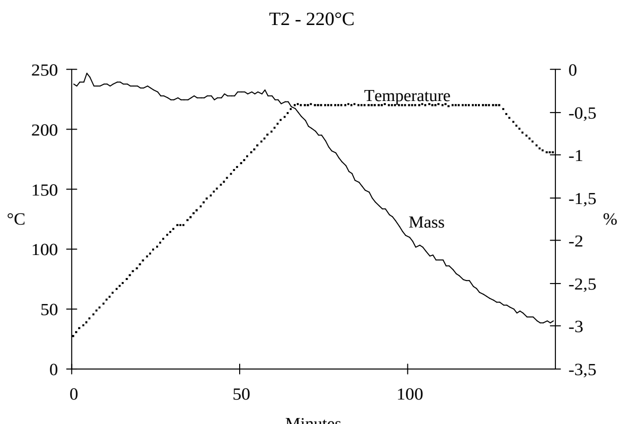

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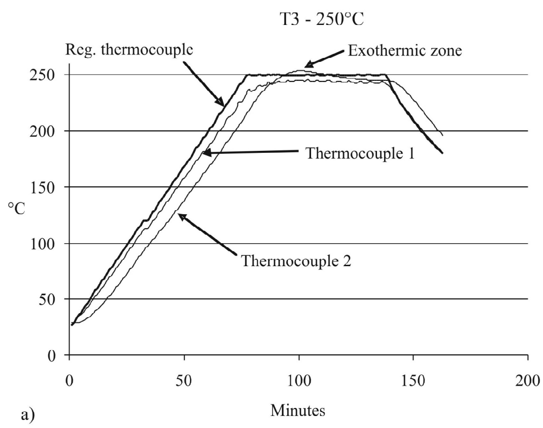
Figure 2 – Graphs of (a) temperatures and (b) loss of mass *x* temperature, 220°C.

***Figura 2** – (a) Gráficos das temperaturas; (b) perda de massa x temperatura, 220°C.*



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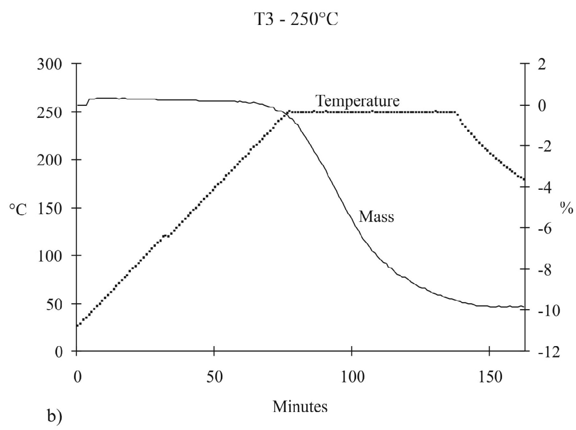

b)

Figure 3 – Graphs of (a) temperatures and (b) loss of mass *x* temperature, 250°C.

***Figura 3** – (a) Gráficos das temperaturas; (b) perda de massa x temperatura, 250°C.*

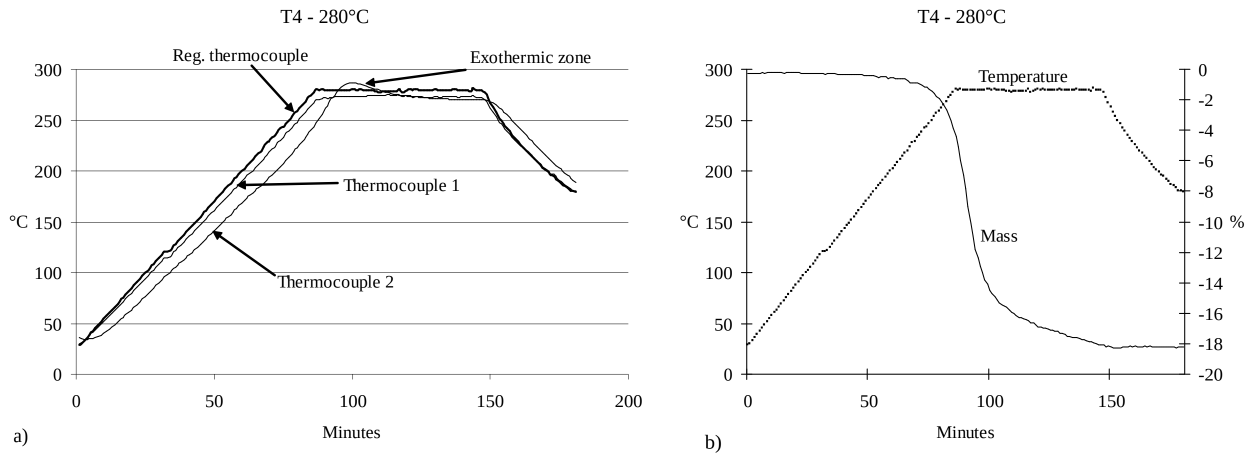

Figure 4 – Graphs of (a) temperatures and (b) loss of mass *x* temperature, 280°C.

***Figura 4** – (a) Gráficos das temperaturas; (b) perda de massa x temperatura, 280°C.*

Table 3 – Bulk density (dry basis) of *Eucalyptus grandis* wood in three different treatments.

***Tabela 3 –** Densidade aparente (base seca) da madeira de Eucalyptus grandis sob três tratamentos*

Treatment	Bulk density (g/cm^3)	Percentage loss (%)
Control*	0.85a	—
T2 – 220°C	0.83a	2.35
T3 – 250°C	0.79b	7.06
T4 – 280°C	0.73c	14.12

Note: Means followed by the same letter are statistically similar at the 5% probability level.
* Average moisture content of control treatment = 15%.

The temperature of treatment 2 (220°C) was insufficient to cause significant changes in bulk density. In other treatments, however, the increase in temperature led to a significant decrease in that property, resulting primarily from loss of mass.

Higher heating value (HHV), lower heating value (LHV) and useful heating value (UHV) are depicted in Table 4. Percentage increases appearing next to each treatment refer to HHV and UHV increases, in relation to the control.

Despite not mentioning temperatures, Doat (1985) found HHV value of 22 to 25 MJ/kg for torrefied wood. Arias et al. (2008) found HHV values of 22.8 MJ/kg at 260°C and 25.0 MJ/kg at 280°C for *Eucalyptus sp.*, both treated for 60 minutes. Felfli & Luengo (2005) found values of 20.99 MJ/kg at 220°C and 22.06 MJ/kg at 250°C for wood briquettes treated for one hour.

The difference between HHV and UHV is evidenced by the percentage increase each treatment caused in relation to the control. While the maximum increase in HHV was 15.74%, the minimum increase in UHV was 25.70%. The UHV expresses actual conditions of use, therefore explaining the negative reflections of moisture on the energy content of the biomass.

The relationship between bulk density and higher heating value in torrefied wood provides its energy density (ED). The value of useful energy density (useful ED) related bulk density to UHV. For percentage increases, the results of ED and useful ED for torrefied samples were correlated to the control. Table 5 presents results of energy density and energy yield for *E. grandis* wood.

No significant difference was found for any of the treatments regarding energy density. As regards useful energy density, the rise in temperature from one treatment to the next caused it to increase significantly in relation to the control. While the maximum increase in ED was 2.19%, the minimum increase in useful ED was 21.04%. Figure 5 illustrates the difference between these two forms of energy density.

Table 4 – Higher heating value for *E. grandis* wood in three treatments.

***Tabela 4** – Poder Calorífico Superior da madeira de E. grandis sob três tratamentos.*

Treatment	HHV (MJ/kg)	LHV (MJ/kg)	UHV (MJ/kg)	Percentage increase (%)	
				HHV	UHV
Control*	19.57a	18.21	15.10a	-	
T2 – 220°C	20.34b	18.98	18.98b	3.93	25.70
T3 – 250°C	21.44c	20.08	20.08c	9.56	32.98
T4 – 280°C	22.65d	21.29	21.29d	15.74	40.99

Means followed by the same letter are statistically similar at the 5% probability level.
* Average moisture content of control treatment = 15%.

Table 5 – Energy density and energy yield for *E. grandis* wood in three treatments.

***Tabela 5** – Densidade energética e rendimento energético da madeira de E. grandis sob três tratamentos.*

Treatment	ED (GJ/m³)	Useful ED (GJ/m³)	Percentage increase (%)		η_{En}
			ED	Useful ED	(%)
Control*	16.60a	12.84a	-		-
T2 – 220°C	16.92a	15.75b	1.91	22.69	100.19
T3 – 250°C	16.96a	15.86b	2.19	23.55	96.68
T4 – 280°C	16.63a	15.54b	0.19	21.04	92.76

Note: Means followed by the same letter are statistically similar at the 5% probability level.
* Average moisture content of control treatment = 15%.

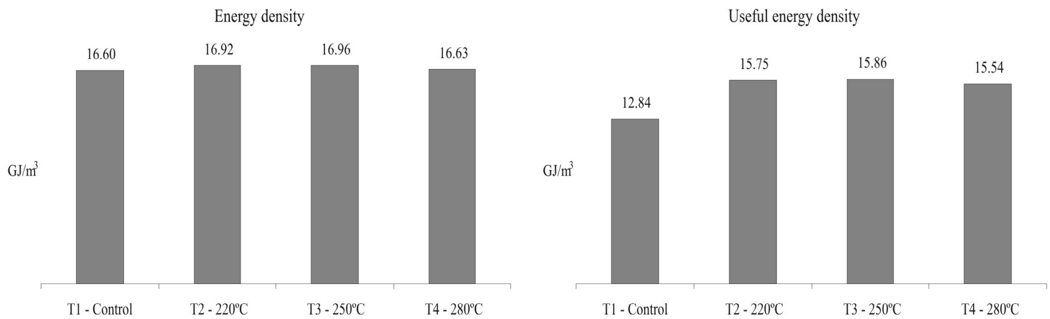

Figure 5 – Energy density and useful energy density for *E. grandis* wood in three treatments.

***Figura 5** – Densidade energética e densidade energética útil da madeira de E. grandis sob três tratamentos.*

The energy yield was high as a function of the also high gravimetric yield and of the significant increase in higher heating value. The energy yield behaved as expected, with 92.76% of the energy content being retained in the wood torrefied at 280°C, which is in agreement with the average energy yield of 90% proposed by Bergman et al. (2005) and Prins et al. (2006). Bridgeman et al. (2008) observed an energy yield of 92.7% in *Salix sp.* wood subjected to treatment at 250°C for 30 minutes.

4 CONCLUSIONS

Torrefaction is an effective treatment for boosting energy levels in *Eucalyptus grandis* wood. In this study, this thermal treatment caused significant changes in wood properties. The temperature of 220°C was insufficient to cause changes in bulk density in relation to the control treatment, while as regards other properties changes were mild. The temperatures of 250°C and 280°C produced fuel with better energy properties than that of feedstock wood. These temperatures increased the higher and lower heating values and, above all, the useful heating value of torrefied wood, since there was no influence of moisture. Effects on the energy density indicate that the temperature of 250°C is most effective. An expressive decrease in mass was observed at 280°C, with negative consequences on bulk density and, consequently, on energy density. The analysis of results denotes that the temperature of 220°C was insufficient to cause changes that would justify its use for energy conditioning of wood. The temperatures of 250°C and 280°C proved effective for the requirements of this study and are definitely recommended for energy conditioning of biomass.

5 BIBLIOGRAPHICAL REFERENCES

ALMEIDA, G. **Valorização energética de resíduos madeireiros mediante a termorretificação**: relatório de atividades, bolsa de pós-doutorado. São Paulo: FAPESP, 2007. 57 p.

ANTAL JUNIOR, M. J.; GRØNLI, M. The art, science, and technology of charcoal production. **Industrial England Chemical Research**, London, v. 42, p. 1619-1640, 2003.

ARIAS, B.; PEVIDA, C.; FERMOSO, J.; PLAZA, M. G.; RUBIERA, F.; PIS, J. J. Influence of torrefaction on the grindability and reactivity of woody biomass. **Fuel Processing Technology**, v. 89, p. 169-175, 2008.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 8633/84**. Rio de Janeiro, 1984.

BERGMAN, P. C. A.; BOERSMA, A. R.; KIEL, J. H. A.; PRINS, M. J.; PTASINSKI, K. J.; JANSSEN, F. J. J. G. **Torrefaction for entrained-flow gasification of biomass**. Netherlands: ECN, 2005. 51 p.

BRIDGEMAN, T. G.; JONES, J. M.; SHIELD, I.; WILLIAMS, P. T. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. **Fuel**, v. 87, p. 844-856, 2008.

COPANT. **Copant 461-1972**: maderas: método de determinación del peso específico aparente. Caracas, 1972.

DOAT, J. Un nouveau produit énergétique pour les pays en développement: le bois torréfié. **Revue Bois et Forets des Tropiques**, n. 208, p. 57-67, 1985.

FELFLI, F.; LUENGO, C. A. Wood briquette torrefaction. **Energy for Sustanaible Developpement**, v. 9, n. 3, p. 19-22, 2005.

GIRARD, P.; SHAH, N. Recent developments on torrefied wood, an alternative to charcoal for reducing deforestation. **REUR Technics Series**, v. 20, p. 101-114, 1991.

HAKKOU, M.; PETRISSANS, M.; GERARDIN, P.; ZOULALIAN, A. Investigations of the reasons for fungal durability of eat-treated beech wood. **Polymer Degradation and Stability**, v. 91, p. 393-397, 2006.

INARI, G. N.; MOUNGUENGUI, S.; DUMARÇAY, S.; PÉTRISSANS, M.; GÉRARDIN, P. Evidence of char formation during wood heat treatment by mild pyrolysis. **Polymer Degradation and Stability**, v. 92, p. 997-1002, 2007.

KOLLMANN, F. F. P. **Principles of wood science and technology**. New York: Springer-Verlag, 1984.

MBURU, F.; DUMARÇAY, S.; PETRISSANS, M.; GÉRARDIN, P. Evaluation of thermally modified Grevillea robusta heartwood as an alternative to shortage of wood resource in Kenya: characterisation of physicochemical properties and improvement of bio-resistance. **Bioresource Technology**, Oxford, v. 98, n. 18, p. 3478-3486, 2007.

PRINS, M. J.; PTASINSKI, K. J.; JANSSEN, F. J. J. G. Torrefaction of wood part 1: weight loss kinetics. **Journal Analitical Applied Pyrolysis**, v. 77, p. 28-34, 2006.

ROUSSET, P. L. A. **Choix e validation experimentale d'un modele de pyrolyse pour le bois traite par haute temperature**: de la micro-particule au bois massif. 2004. 203 f. Tese (Doutorado) - LERMAB, ENGREF, Nancy, 2004.

ROWELL, R. M.; PETTERSEN, R.; HAN, J. S.; ROWELL, J. S.; TSHABALALA, M. A. Cell wall chemistry. In: ROWELL, R. M. (Ed.). **Handbook of wood chemistry and wood composites**. Boca Raton: CRC, 2005. p. 35-74.