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Scientific Article

CARBONIZATION GASES AS AN ENERGY SOURCE FOR *Eucalyptus* LOGS DRYING OF DIFFERENT DIAMETER CLASSES IN METALLIC DRYER

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ABSTRACT

The wood carbonization with high moisture content reduces the yield, prolongs the carbonization time and results in charcoal with low mechanical strength. Considering this, the reuse of carbonization gases as a source of thermal energy becomes a potential alternative for reducing moisture content quickly and feasibly. The objective of this study was to evaluate the artificial drying of logs using gases from the carbonization system of a furnace and a drying chamber. The drying evaluation was conducted in duplicate using a 35 m³ galvanized metal square dryer and a furnace with a useful volume capacity of 16.8 m³. The average gas intake temperature for drying was 150°C. The eucalyptus logs were divided into three diameter classes (8-14 cm; 14-22 cm; 8-22 cm). The electricity consumption of the dryer was approximately 49.4 kW per ton of wood (dry mass). The highest thermal efficiency was achieved in the drying of 814 cm diameter class logs. The utilization of carbonization gases proved to be effective in reducing wood moisture in all diameter classes, showing potential for large scale utilization.

Keywords: Moisture content; Charcoal; Sustainability; Thermal efficiency

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GASES DA CARBONIZAÇÃO COMO FONTE DE ENERGIA PARA SECAGEM DE MADEIRA DE *Eucalyptus* DE DIFERENTES CLASSES DE DIÂMETRO EM SECADOR METÁLICO

RESUMO – A carbonização da madeira com alto teor de umidade reduz o rendimento, prolonga o tempo de carbonização e resulta em carvão vegetal com baixa resistência mecânica. Diante disso, o reaproveitamento dos gases da carbonização como fonte de energia térmica se torna uma alternativa em potencial para redução do teor de umidade de forma rápida e viável. O objetivo deste estudo foi avaliar a secagem artificial de toras utilizando gases do sistema de carbonização de um forno e uma câmara de secagem. A avaliação da secagem foi realizada em duplicata utilizando um secador quadrado de metal galvanizado de 35 m³ e um forno com capacidade volumétrica útil de 16,8 m³. A temperatura média de admissão dos gases para a secagem foi de 150 °C. As toras de eucalipto foram divididas em três classes de diâmetro (8-14 cm; 14-22 cm e; 8-22 cm). O consumo de eletricidade do secador foi aproximadamente de 49,4 kW por tonelada de madeira (massa seca). A maior eficiência térmica foi alcançada na secagem de toras da classe de diâmetro de 8-14 cm. A utilização de gases de carbonização se mostrou eficaz na redução da umidade da madeira nas três classes de diâmetro, mostrando potencial para utilização em larga escala.

Palavras-Chave: Teor de umidade; Carvão vegetal; Sustentabilidade; Eficiência térmica

1. INTRODUCTION

Eucalyptus wood is the genus with the largest share in charcoal production and widely used in Brazil for energy generation. Its average productivity of 32.7 m³/ha/year and an area of 7.60 million hectares make these forests the most productive in the world (IBÁ, 2023). Extremely relevant to the Brazilian economy and the forestry sector, charcoal is mainly obtained from the slow pyrolysis process of wood from planted forests. However, to fulfill the demands of the charcoal production chain and consuming industries, the wood must have a series of desirable physical, anatomical, and chemical characteristics to ensure the quality of the final product, such as the moisture content. Therefore, it is necessary to dry the material for energy generation purposes (combustion, gasification, or pyrolysis), increasing its calorific value, process yield, energy efficiency, and reducing pollutant emissions (Assis et al., 2016; Schettini et al., 2022)

Wood drying is a complex process due to the heterogeneity of the wood and the different forms of interaction with water (Klement et al., 2020). Free water is connected through weak capillary bonds in the empty spaces of the wood and is the first to be removed from the wood due to its low energy requirement for removal (Penvern et al., 2020). Hygroscopic water is connected to the wood through stronger hydrogen bonds, and its removal occurs in the advanced stages of drying, requiring a higher amount of energy (Zanuncio et al., 2022). In this context, it is necessary to adapt the drying process to its characteristics and stage (Tulej et al., 2021).

Knowledge of the physical properties of lignocellulosic materials is essential for the study of processes based on thermal treatment, such as the carbonization process. Heat transfer, during the drying stage, for example, can be influenced by the thermal conductivity of the wood, diameter, moisture content, density, chemical composition, porosity, and another variables. The diameter of the wood is the variable that most influences the heat transfer between the raw material and the environment, and the larger the diameter, the longer it takes for the heat flow to reach the inner regions of the wood (Jesus et al., 2019; Ramos et al., 2021).

Drying is one of the major challenges in the process of wood carbonization for charcoal production (Canal et al., 2020; Figueiró et al., 2020), aiming to achieve a material with up to 40% moisture content on a dry basis (Braz et al., 2015; COPAM, 2018; Zen et al., 2019). The most commonly adopted method is natural air drying, near the planting site, to take advantage of solar energy and save on forest transportation, typically extending for 90 to 150 days. However, even with this duration, the wood may still have high moisture content, and the high demand for this material may make waiting for such a long time impractical (Braz et al., 2015; Figueiró, 2022; Pertuzzatti et al., 2013; Zanuncio et al., 2013). In addition to longer drying time, the natural drying method is dependent on edaphoclimatic conditions, as well as the arrangement and stacking of the wood piles. Other challenges are also observed, such as the long time capital is stagnated in the field and the dry mass losses due to various factors, such as pathogen attacks and wood decay in the field (Zanuncio et al., 2013). In this context, there is a demand for the use of artificial methods for drying logs intended for charcoal production.

The development of log dryers for charcoal production is still in its early stages. However, the possibility of harnessing the energy generated during the material's carbonization process for the dryers is a technically and economically viable alternative. The development of gas burners can reduce drying time, decrease the wood moisture contente before carbonization, improve the charcoal mechanical strength, and reduce carbonization time and pollutant emissions (Figueiró et al., 2020). The carbonization gases, which are partly composed of combustible compounds, are burned in the gas burner connected to drying systems, heating the wood and providing energy for the drying process to occur (Figueiró, 2022). The utilization of dryers should take into account the material's moisture content and wood characteristics, such as, density, permeability and diameter.

The objective of this study was to evaluate the performance of a metal dryer coupled with a kinl-furnace system in reducing the moisture content of eucalyptus logs of different diameter classes, using carbonization gases as an energy source.

2. MATERIAL AND METHODS

2.1 Description of metallic dryer

The dryer (Figure 1) was constructed using 2.00 mm galvanized metal and walls with a 40 mm thickness, insulated with aluminized ceramic fiber. The internal dimensions of the metallic dryer were 2.50 m height, 0.70 m dome height, 4.20 m length, and 3.10 m width. The total volume of the dryer was 35 m³, and the volume used for drying the wood was 16.8 m³. The dryer's roof was made with a cylindrical-shaped section to facilitate the flow of combustion gases within the dryer. The dryer doors were made in the form of flaps, also thermally insulated with ceramic blanket (Figure 1A).

On the wall opposite the door, a main distributor of combustion gases, with internal diameter of 150 mm and a height of 2.00 m above the floor, was installed at the top and had four secondary dampers for better distribution of the hot gas flow inside the dryer (Figura 1B).

Three axial fans were also installed on the opposite side of the door. These were individually driven by 0.5 hp motors and were designed to promote a better distribution of the combustion gases inside the dryer (Figure 1C). On the lower part of the same wall, four dampers with a diameter of 150 mm were made for the exhaust of the moist gases from inside the dryer. The openings were connected to a single 5 hp centrifugal fan for exhaust. All fans used in the system were connected to a single electrical panel with independent control (Figura 1D).

2.2 Description of the gas transportation system

The metal dryer was connected, via a stainless-steel pipe, to the kinl-furnace system, responsible for supplying thermal energy derived from the gases of carbonization burned in the gas burner.

The temperature of the gases at the exit of carbonization oven was 500°C, so it was necessary to use an air mixer to reduce it to 150°C, the temperature used for artificial wood drying (Figure 2). The combustion gases were extracted through a stainless-steel pipe, with 2.20 meters height, which was connected to the mixer built with solid bricks next to the base of the furnace. A tube made of galvanized sheets with an internal diameter of 150 mm was installed at the top of the mixer to transport the gases from the carbonization furnace to the dryer. This tube was connected to a 3 hp centrifugal fan responsible for suctioning the combustion gases from the mixer to the dryer. In the same tube, positioned 1.5 meters from the ground, a manually operated 12 x 15 cm opening was used to control the temperature of the gases at the dryer inlet (Figura 2.4).

2.3 Artificial drying of wood using combustion gases

Revista ÁRVORE
ISSN 1806 – 9088

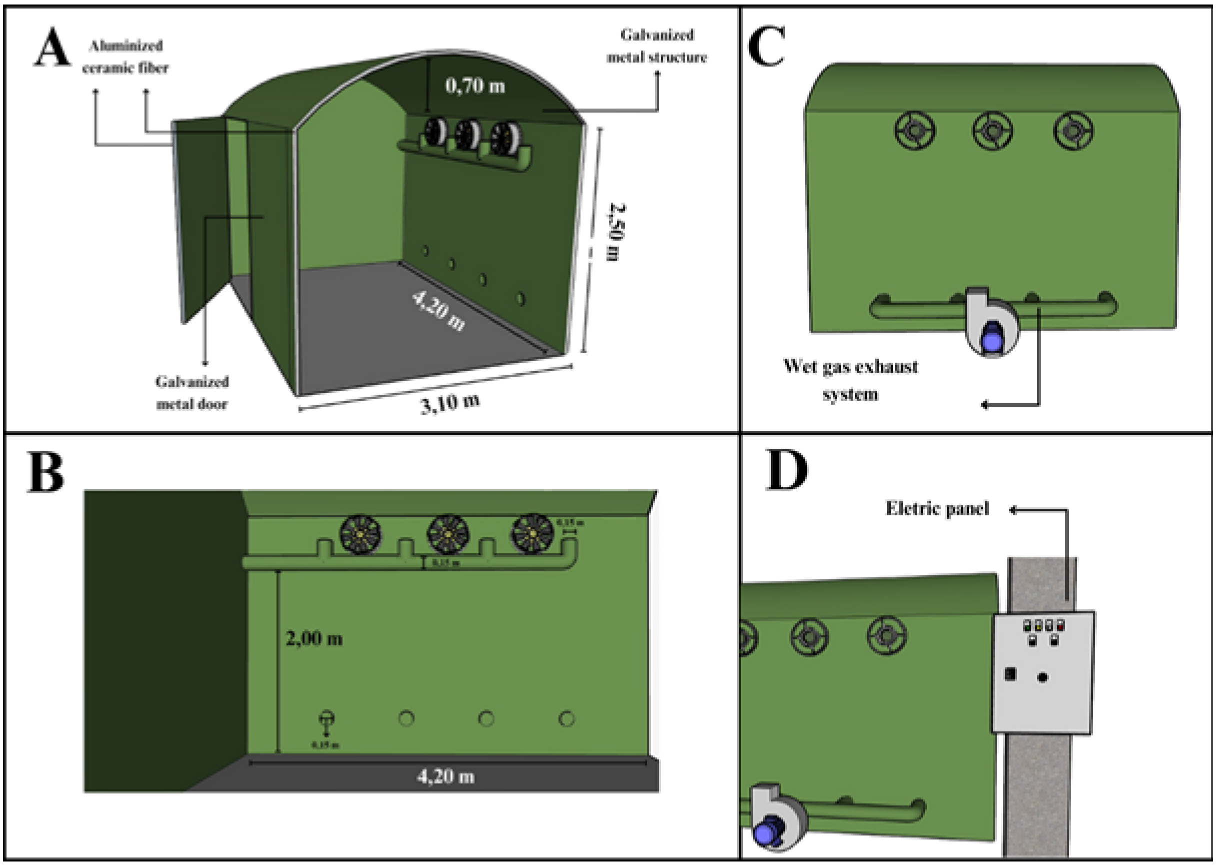

Figure 1. A - Overview of the dryer; B - details of the positioning of the distributor of combustion gases, axial fans, and wet air outlets; C- pipe detail and centrifugal exhaust fan of moist air; D – Panel control

Figura 1. A – Vista geral do secador; B – detalhes do posicionamento do distribuidor de gases de combustão, ventiladores axiais e saídas de ar úmido; C – detalhe da tubulação e exaustor centrífugo de ar úmido; D – Painel de comando

The temperature profile in the dryer was controlled by 16 sensors distributed throughout the drying chamber, two points on the dome, three points on each side wall, two points on the door, and six points on the back of the dryer, in front of the door (Figure 3).

The drying process lasted approximately 68 hours, using gas at 150°C obtained from carbonization in the furnace. This duration was established based on the average total carbonization time of the wood in this system. The logs were separated into three diameter classes: Class 1 (8 to 14 cm); Class 2 (14 to 22 cm); and Class 3: (8 to 22 cm), with the last class containing a proporcional mixture of diameters belonging to Classes 1 and 2, based on the weight of the wood. The diameter classes were determined based on the usual diameter ranges used by charcoal-producing companies. Two batches were carried out for each diameter class.

The logs were weighed before and after drying using a Digi-Tron UDL 3000 scale, with a maximum capacity of 3 t, to obtain the mass of water removed.

Forty-five control logs were selected and distributed at nine points in the furnace, as shown in Figure 4. To determine the moisture content on a dry basis, the wood control samples were weighed individually before and after drying. Three disks were removed from each sample (log) along its length, with one disk in the center and the other two equidistantly 50% from the center to the end. The moisture content was determined by the oven method at 103±2°C until a constant weight was achieved. To estimate the initial moisture content of each control log, Equation 1 and 2 was used.

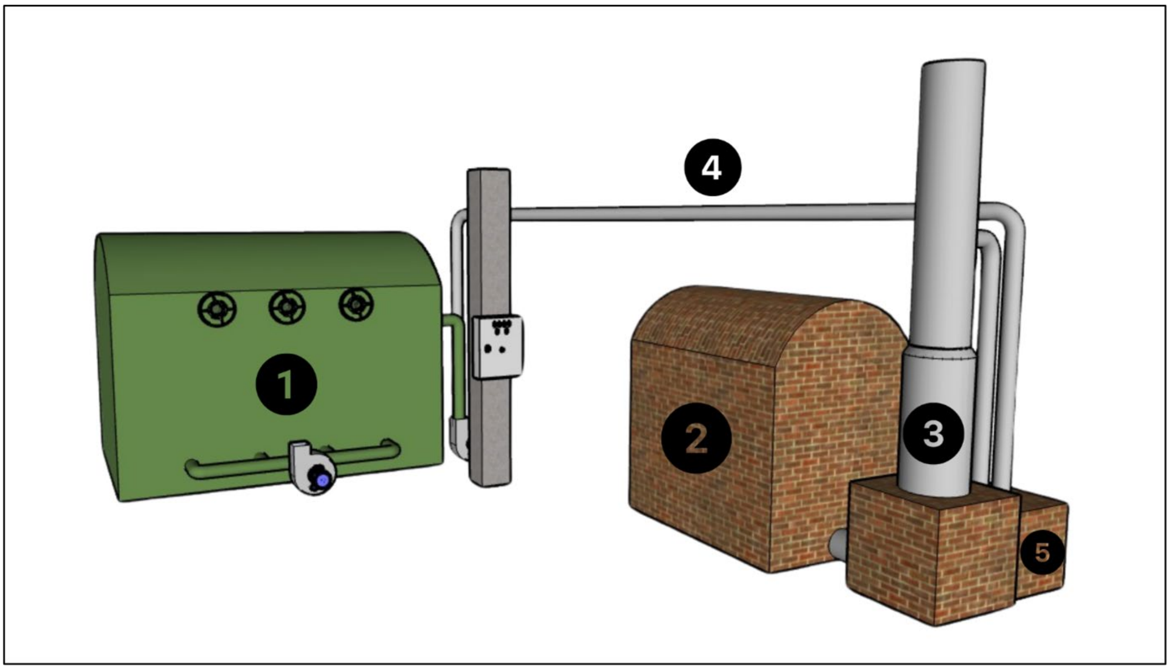

Figure 2. Overview of kiln-furnace system and drying system, being: 1 - Dryer; 2 - Kiln; 3 - Furnace; 4 - Gas transport network; and 5- Mixer

Figura 2. Visão geral do sistema forno-fornalha e sistema de secagem, sendo: 1 - Secador; 2 - Estufa; 3 - Fornalha; 4 - Rede de transporte de gases; e 5- Misturador

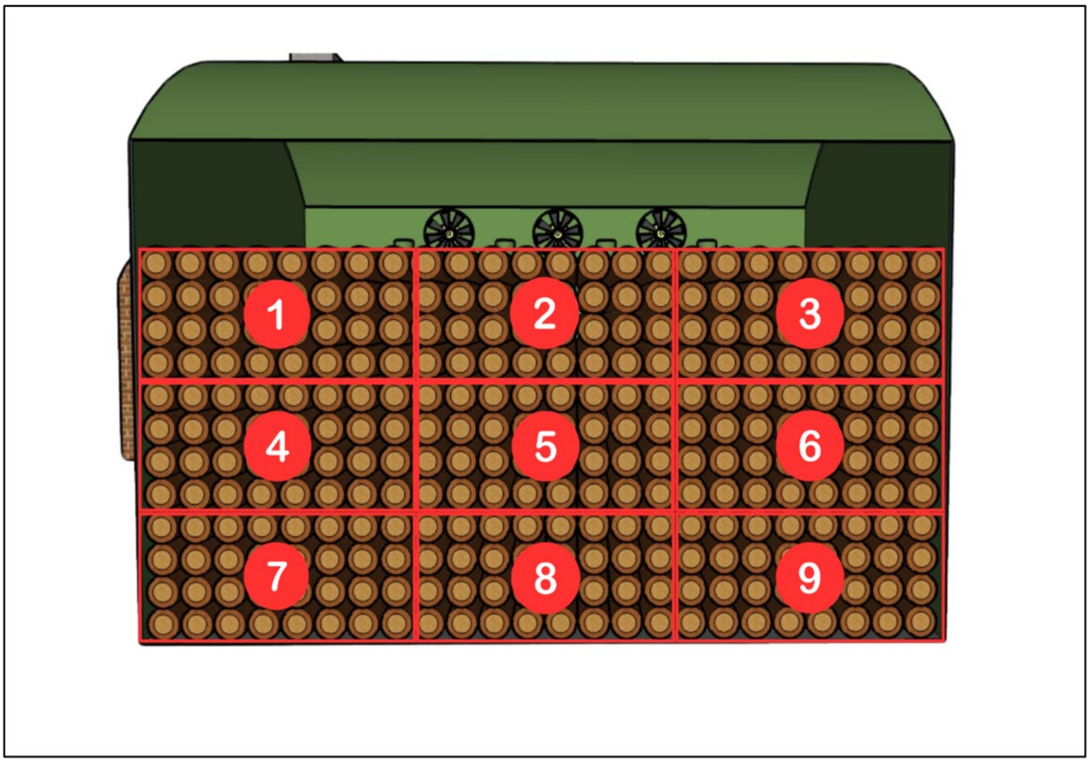

Figure 3. Strata division for log selection for moisture control

Figura 3. Divisão de estratos para seleção de toras para controle de umidade

Revista ÁRVORE
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$$Md = Maf/1 + Ma/100 \quad \text{(Eq. 1)}$$

In wich:

Md - Estimated dry mass of the log (control sample) (kg);

Maf - mass of the log (control sample) after drying (kg);

Ma - average moisture content of the disks (%);

Once the dry mass value was obtained, the initial moisture content of each wood log (control sample) was estimated according to Equation 2.

$$Mi = (Mb - Md/Md) * 100 \quad \text{(Eq. 2)}$$

In wich:

Mi = estimated initial moisture content (%);

Mb = mass of the wood log before drying (kg);

Md = estimated dry mass of the wood log (kg)

The drying rate (kg of water/kg of wood per hour) was determined by dividing the mass of water removed by the dry mass of the wood stacked in the dryer. This procedure was carried out for each diameter class. The moisture loss (%) was calculated using the following equation 3:

$$Ml = Mi - Mf/Mi * 100 \quad \text{(Eq. 3)}$$

In which:

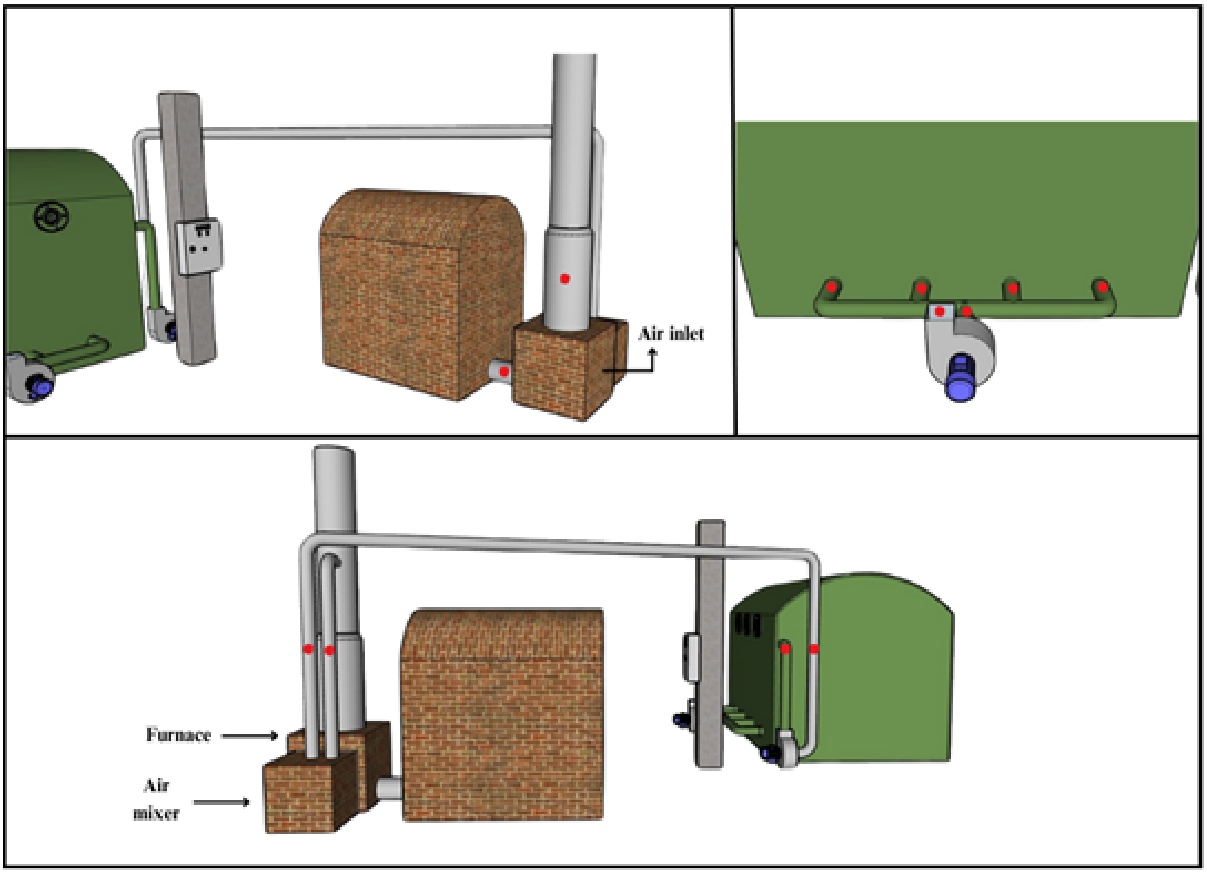

Figure 4. Points location (red dot) for temperature collection

Figura 4. Localização dos pontos (ponto vermelho) para coleta de temperatura

Ml - Moisture loss (%);

Mi - Initial moisture content (kg);

Mf - Final moisture content after drying (kg).

cp - Specific heat of gas (J/(kg.K));

Tout - Exhaust gas temperature (K);

Tin - Combustion gas inlet temperature (K).

2.4 Analysis of combustion gas temperature

The monitoring points were allocated along the passage of the combustion gases from the carbonization furnace to the dryer, allowing for the evaluation of thermal losses and system efficiency (Figure 3).

The temperature distribution in the pipeline connecting the mixer to the dryer was evaluated using infrared thermographic images taken with an infrared camera (FLIR 40) with an emissivity factor of 0.95. The images were captured from a distance of 10 meters from the system.

2.5 Monitoring of temperature losses

The thermal losses in the gas transport from the carbonization furnace were calculated considering the system with constant properties, ideal gas behavior, and neglecting viscous dissipation, variations in static pressure, and thermal resistance of the piping.

For calculating the temperature difference between the combustion gases at the inlet and outlet of the tube, first, the sensible heat due to temperature variation was considered, according to Equation 4.

$$q = mc_p\,(T_{out} - T_{in}) \qquad \text{(Eq. 4)}$$

In relation to the volumetric flow rate, Equation 5 was obtained.

$$q = \rho Q_{cp}\,(T_{out} - T_{in}) \qquad \text{(Eq. 5)}$$

In which:

q - Heat transfer rate (W);

ρ - Specific mass of the gas (kg/m³);

Q - Volumetric flow rate (m³/s);

Considering also that the heat transfer is a function of the temperature gradient and the resistance of the system to this flow, Equations 6 and 7 was obtained.

$$q = \Delta T_{m,l}/Rt \qquad \text{(Eq. 6)}$$

In which:

$$\Delta T_{m,l} = T_{out} - T_{in}/\ln(T_\infty - T_{out}/T_\infty - T_{in}) \qquad \text{(Eq. 7)}$$

In which:

ΔTm,l - Logarithmic mean of the temperature differences (K);

Rt - Total thermal resistance of the system (K/W);

T∞ - External fluid temperature (K).

The approach defined for the total thermal resistance of the system was a series circuit followed by a parallel circuit. In this approach, first, there is the thermal resistance for heat conduction from the combustion gases in the tube wall, and subsequently, a parallel circuit in which there is heat loss from the tube wall to the surroundings through convection and radiation, simultaneously.

Therefore, Equations 8, 9, 10, 11 was obtained.

$$R_t = R_{conv,int} + (1/Rrad + 1/R(conv,ext))^{-1} \qquad \text{(Eq. 8)}$$

In which:

$$R_{conv,int} = 1/h_x A_{int} \qquad \text{(Eq. 9)}$$

$$R_{rad} = 1/h_r A_{ext} \qquad \text{(Eq. 10)}$$

$$R_{conv,int} = 1/hA_{ext} \qquad \text{(Eq. 11)}$$

Revista ÁRVORE
ISSN 1806 – 9088

In which:

hx - Internal convection coefficient (W/(m²K));

hr - Radiation coefficient (W/(m²K));

h - External convection coefficient (W/(m²K));

Aint - Internal area in the cylinder (m²);

Aext - External area of the cylinder (m²).

Considering an external convection coefficient of 20 W/(m²K), the radiation coefficient was estimated according to Equation 12.

$$hr = \varepsilon\sigma(T_{surf} + T_{surr})(T_{surf}^2 + T_{surr}^2) \quad \text{(Eq. 12)}$$

In which:

ε - Emissivity of the material;

σ - Stefan-Boltzmann constant (s=5.67E-8 W/(m²K));

Tsurf - Surface temperature (K);

Tsurr - Temperature of the surroundings (K).

As the surface temperature is not known, it was stipulated through interactions. The internal convection coefficient was estimated according to Equations 13 and 14.

$$Nu_d = hxD/k = 0.023 Re_d^{4/5} Pr^n \quad \text{(Eq. 13)}$$

Where,

$$Re_d = \rho VD/\mu \quad \text{(Eq. 14)}$$

In which:

Nud - Nusselt number;

D - diameter (m);

k - thermal conductivity of the gas (W/(mK));

Red - Reynolds number;

μ - gas viscosity (Ns/m²);

Pr - Prandtl number;

n - 0.3, since it is cooling.

Equating equations 6 and 7, Equation 15 was obtained.

$$q = \rho Q c_p (T_{out} - T_{in}) = T_{out} - T_{in} / Rt \ln(T_\infty - T_{out} / T_\infty - T_{in}) \quad \text{(Eq. 15)}$$

As this is an implicit equation, the value of the combustion gas temperature at the outlet of the gas transport pipeline was obtained through an iterative process. Thus, once the outlet temperature is known, the amount of energy transferred to the surrounding areas by Equation 3 was calculated.

2.6 Mass and energy balance

2.6.1 Electricity consumption of the dryer

A FAE MFA-04G analog three-phase consumption meter was installed in the central electrical panel to obtain the energy consumed by the system during the 68 hours of dryer operation. The total electricity consumption was determined, and the average consumption for each drying cycle was defined using arithmetic mean.

The specific electrical energy was obtained by dividing the average electricity consumption of the dryer by the dry mass of the wood (0% moisture), in order to obtain the value in kW per ton of wood.

2.6.2 Thermal efficiency of the dryer

To determine the thermal efficiency of the dryer, the amount of energy in the form of sensible heat provided for drying was calculated using the Equation 16.

$$Q = V.\rho.cp.\Delta t \quad \text{(Eq. 16)}$$

In which:

Q - Sensible heat supplied for drying (J/s);

V - Gas flow rate at the inlet of the dryer (m^3/s);

ρ - Density of the gas mixture (g/m^3);

cp - Specific heat of air (kJ/(kg*K));

Δt - Temperature difference between the gases at the inlet and outlet of the dryer (K).

The gas flow at the inlet of the dryer was measured using a Pitot tube. The specific heat of the gases was obtained from the literature (Incropera et. al., 2011) for each temperature range used.

The mass of water removed in the drying process was used to estimate the amount of energy required to remove the water from the wood for each evaluated diameter class, separating the percentage of free water and adsorption water. For this procedure, the free water was above 30% moisture content, while the adsorption water was below that threshold.

This distinction was necessary as the removal of free water consumed approximately 569 kcal/kg, while the removal of adsorption water consumed approximately 829 kcal/kg (Skaar, 1972).

The specific thermal energy (J/s per ton of wood) was determined by dividing the energy supplied for drying, which corresponds to the sensible heat, by the mass of dry wood. The thermal efficiency was determined by dividing the energy supplied for drying by the energy that was effectively used in the removal of the water mass.

2.7 Production and properties of charcoal

2.7.1 Technical Parameters of Carbonizations

Six wood carbonizations were carried out, which provided the gases for combustion in the furnace for drying. In this case, the thermal energy from the combustion of the gases was used to perform the drying. The carbonizations were conducted with wood separated by diameter classes, according to the classification used for drying. However, it should be noted that these were independent samples, meaning they did not undergo the drying process.

Each carbonization was conducted for 14 hours up to 150°C; 14 hours between 150 and 275°C; 24 hours between 275 and 400°C; and 20 hours between 400 and 420°C, totaling 72 hours of carbonization. The carbonization curve for process control was based on the characteristics of the furnace and the theoretical phases of thermal degradation of the wood according to the recommendations of Oliveira et al. (2013) and Gomes et al. (2020).

The operation of the furnace was monitored to ensure uninterrupted combustion of the carbonization gases, providing the combustion gases for drying. For this purpose, wood residues were supplied to the furnace whenever necessary to keep the flame burning in the combustion chamber.

The gravimetric yield of charcoal was determined by the Equation 16.

$$CGY = 100\, x\, Mc/\mathrm{Mw} \qquad \text{(Eq. 17)}$$

In which:

CGY - Gravimetric yield of charcoal (%);

Mc – Mass of charcoal(kg); and

Mw - Mass of air-dried wood (kg).

2.7.2 Estimation of gravimetric charcoal yield increase

The mass of wood that would no longer be used in carbonization to provide energy for wood drying inside the furnace was considered to estimate the increase in the gravimetric yield of charcoal in each diameter class.

The increase in the gravimetric yield of charcoal was estimated based on the amount of energy required to remove water from the wood. This was done by dividing the obtained value for each diameter class by 3600 kcal/kg, which corresponds to the average useful calorific value of wood with a moisture content of 30% (dry basis). Thus, the mass of wood necessary for combustion is determined. This mass was converted into charcoal, using the obtained value of the gravimetric yield for each diameter class. This result was added to the mass of charcoal already obtained from carbonization to estimate the increase in the gravimetric yield of charcoal.

2.7.3 Sampling and charcoal Properties

After each carbonization, 50 kg of charcoal were collected, which were spread out on a plastic screen and homogenized. Then, the charcoal was divided into four parts (quadrant), with two parts discarded and the other two parts used to obtain sufficient samples for analysis.

The bulk density was determined according to the procedures of ABNT NBR 6922 (ABNT, 1981). The determination of volatile matter (VM), ash (AS), and fixed carbon (FC) was carried out according to the recommended procedures in ABNT NBR 8112 (ABNT, 1986). To determine the friability and classification of charcoal in terms of fines generation, the procedures described by Oliveira et al. (1982) were used.

3. RESULTS

3.1 Combustion Gas Analysis

The average temperature of the combustion gases varied according to the diameter classes 1 (8 to 14 cm), 2 (14 to 22 cm), and 3 (8 to 22 cm), as well as between different monitoring points, with higher temperatures in the furnace combustion chamber (Table 1).

3.2 Effect of Diameter Class on wood Drying

The dryer was effective in reducing wood moisture, regardless of the diameter class. However, Class 1, with smaller diameter logs, showed a greater moisture loss during drying (Table 2).

3.3 Gravimetric yield and charcoal properties

There was no difference in charcoal yield and quality among the carbonization processes

Table 1. Average temperatures of the gases

Tabela 1. Temperaturas médias dos gases

Monitoring Points	Mean Temperature (°C)		
	Class 1	Class 2	Class 3
Temperature of the kiln exhaust gases	80.1±50.2	73.8±40.2	104.2± 64.6
Furnace combustion chamber temperature	756.3±171.5	783.5±157.2	654.1±120.4
Combustion gas temperature at the air mixer inlet	433.9±105.6	471.8±126.6	450.1±105.6
Gas temperature at outlet of air mixer	323.1±72.4	344.2±58.1	298.3±63.9
Gas temperature before the air inlet opening (control)	261.9±49.7	258.1±34.0	231.3±32.5
Combustion gas temperature at the dryer inlet	159.9±14.8	155.8±7.5	153.4±7.3
Average dryer gas outlet temperature (wet gas)	60.4±11.2	57.8±7.4	49.4±8.0
Gas temperature before the blower fan	58.3±10.3	55.6±7.0	48.5±7.5
Gas temperature after the blower fan	54.4±9.9	50.7±8.4	48.3±7.6

* The values after the ± sign represent the standard deviation of the mean.

Table 2. Mean parameters of the wood by diameter class, obtained after drying

Tabela 2. Parâmetros médios da madeira por classe de diâmetro, obtidos após secagem

Diameter class	Dry wood mass (kg)	Water mass re-moved (kg)	Drying rate (kg water/kg wood.h)	Initial moisture content (%)	Final moisture (%)	Relative decrease (%)
1	4314.4	1281.35	0.00436	70.81	42.96	39.34
2	4460.5	554	0.00183	84.46	61.29	27.43
3	4132.5	707.1	0.00252	39.99	22.96	42.58

Diameter class: class 1 (8 a 14 cm); class 2 (14 a 22 cm); class 3 (8 a 22 cm)

Classe de diâmetro: classe 1 (8 a 14 cm); classe 2 (14 a 22 cm); classe 3 (8 a 22 cm)

from Classes 1, 2, and 3. Therefore, the values are presented collectively (Table 3).

3.4 Energy balance of drying and estimation of charcoal yield gain

The total electricity consumption was 850 kW, with an average consumption of 212.5 kW per drying cycle and 49.4 kW per dry ton of wood mass. This energy was consumed during 68 consecutive hours of operation of the drying system, including two centrifugal fans and three axial fans (Table 4).

The Table 5 presents the estimated average energy demand for water removal in wood, considering free water and adsorption water, and the gain in charcoal gravimetric yield.

4. DISCUSSION

4.1 Analysis of combustion gases

The average temperature in the furnace combustion chamber (Table 1), regardless of the wood diameter class, was above 650°C. The combustion chamber temperature must be main-tained above this value to allow the complete combustion of pyrolysis liquor and CO and CH_4 gases, transforming them into CO_2 and H_2O, and reducing particulate matter, as observed by Oliveira (2012), thereby ensuring the combustion efficiency of gases in the sys-tem used. Figueiró (2022) in studying the artificial wood drying for carbonization, used temperatures above 650°C in the combustion chamber to maintain the inlet temperature in the dryer.

The carbonizations were conducted with

Table 3. Mean values of charcoal gravimetric yield and properties

Tabela 3. Valores médios do rendimento gravimétrico e propriedades do carvão vegetal

Charcoal Property (%)	Mean Values with SD
Charcoal gravimetric yield (%)	30.9±2.7
Fines (%)	4.13± 0.35
Semi carbonized wood (%)	5.08± 0.29
Bulk density (kg/m³)	156.15±9.56
Friability	10.8±1.7
Fixed Carbon (%)	77.7±2.4
Volatile Materials (%)	21.1±1.9
Ash (%)	0.99±0.17

Revista ÁRVORE
ISSN 1806 – 9088

Table 4. Parameters of energy efficiency in the utilization of carbonization gases in wood drying

Tabela 4. Parâmetros de eficiência energética na utilização de gases de carbonização na secagem de madeira

Diameter Class	Power supplied (J/s)	Energy utilized (J/s)	Intensive termal Energy (J/s.ton. dry wood)	Intensive electrical energy (kW/t. dry wood)	Thermal efficiency
1	20305	12470	4707	49.3	0.61
2	20330	5388	4558	47.6	0.27
3	22480	7979	5440	51.4	0.36
Mean	21038	8612	4902	49.4	0.41

Table 5. Estimated energy demand for the removal of water from the wood and gain in charcoal gravimetric yield (CGY)

Tabela 5. Estimativa da demanda energética para remoção de água da madeira e ganho no rendimento gravimétrico do carvão vegetal (CGY)

Carbonization	Water mass eliminated during drying (kg)	Energy demand for drying (MJ)	Estimated CGY (%)
1 (class 1)	1181.7	28132,68	36.9
2 (class 1)	1381.0	32877,41	35.9
3 (class 2)	413.2	9837,04	31.3
4 (class 2)	694.2	16526,79	29.8
5 (class 3)	580.2	16018,09	31.9
6 (class 3)	834.0	23024,97	28.3
Mean	847.4	21069,49	32.4

logs separated by diameter classes, according to the classification used for drying, but with samples that did not undergo the artificial drying process. The lower temperature in the combustion chamber of the furnace observed in class 3 may be associated with the higher proportion of larger diameter logs in the carbonization, compared to classes 1 and 2.

Larger diameter logs consumes more thermal energy from the system for its degradation, especially during the drying phase, increasing the endothermic phase of carbonization, as it usually has a higher moisture content than smaller diameter wood (Donato et al., 2020). Additionally, Pereira et al. (2016) mentions that variables such as diameter influence the carbonization time and the quality of gas flow. Considering all the thermal losses that occur during the process of transporting gases from the carbonization furnace to the metal dryer, the inlet temperature of the gases in the dryer can be affected. But, in this work, the variation in the gas temperature at the furnace outlet had no effect on the gas temperature at the dryer inlet, maintaining the pre-established values, as this is controlled by the admission of atmospheric air.

The air mixer is responsible for reducing the temperature of the furnace combustion gases to suitab lelevels for the drying process in the metal dryer by mixing it with atmospheric (cold) air, which is introduced through an air inlet in the mixer. At this point, the average air temperature ranged from 433 to 471°C across the three diameter classes, indicating a temperature drop of approximately 200 to 300°C. This highlights the effectiveness of the mixer in controlling the com-bustion gas temperature.

The inlet gas temperature in the metallic dryer ranged from 153 to 160°C, regardless of the diameter, remaining within the pre-established limit. The temperature reduction was achieved by the air mixer, and the entry of atmospheric air into the system was crucial. Subjecting the wood to the temperatures recorded in the combustion chamber would result in thermal degradation and greater degradation of the metallic dryer's structure. Thus, the air mixer proved to be efficient. Figure 5 shows an infrared thermographic image of the furnace and the gas transport piping to the dryer.

A pattern of increasing temperature of the wet gases exiting the dryer over the drying time was observed. At the beginning of the process, hot gases were introduced into the dryer at an average temperature of approximately 156°C, while the wet gases exiting the dryer were around 30°C. By the end of the drying process, the temperature of the wet gases at the dryer outlet was about 60°C. Therefore, it is noted that the energy transfer in the form of heat from the combustion gases to the wood was higher at the beginning of the drying compared to the end, with a reduction in thermal losses as the exposure time of the gases inside the dryer increased, as observed by Figueiró (2022) in the study of artificial drying of eucalyptus wood. The smaller temperature gradient between the inlet and outlet of the gases reduced the heat transfer between the systems, thereby decreasing thermal losses (Jesus et al., 2019).

The average temperature of the gas outlet from the dryer was 56°C, indicating a temperature reduction of approximately 100°C. Since all the walls of the dryer were insulated, most of the thermal energy was transferred to the logs, favoring the drying process, due to the reduction in thermal losses through the dryer walls.

4.2 Effect of diameter class on drying rate and wood moisture reduction

Overall, after drying, the wood logs reduced their initial moisture content by an average of 36.45%. The class 1 logs showed a drying rate of 0.00436 kg of water/kg of wood.h. Class 3, which consists of a mixture of logs from class 1 and class 2, exhibited an intermediate drying

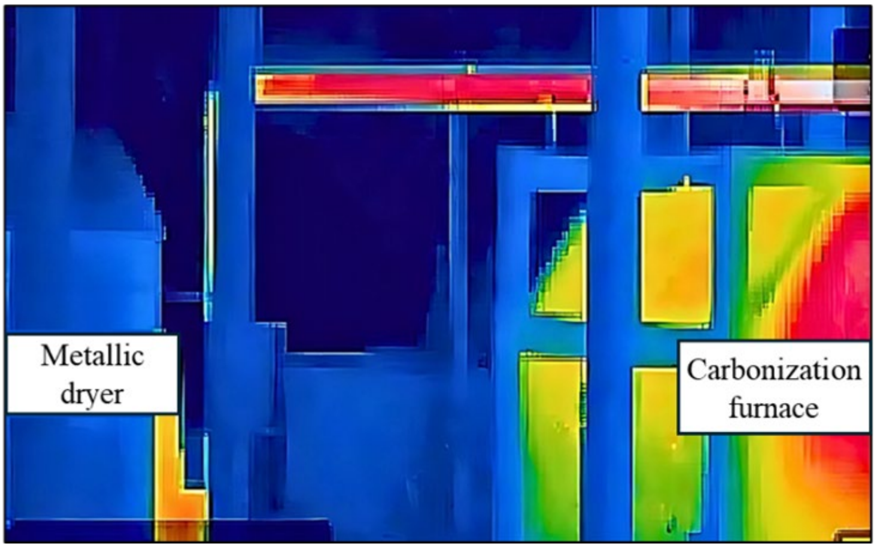

Figure 5. Infrared thermographic image of the furnace and the gas transport piping to the dryer

Figura 5. Imagem termográfica infravermelha do forno e da tubulação de transporte de gás para o secador

Revista ÁRVORE
ISSN 1806 – 9088

rate of 0.00252 kg of water/kg of wood.h. Finally, the logs from class 2, which have a larger diameter (14 to 22 cm), had a drying rate of 0.00183 kg of water/kg of wood.h, even though the final moisture content was high, this indicates that a greater amount of free water was eliminated, highlighting the greater difficulty of drying logs with larger diameters (Table 2).

In Table 2, it can also be observed that the wood logs belonging to classes 1 and 3 achieved a greater reduction in moisture compared to the logs with larger diameters (class 2). It should be emphasized that the drying rate of the logs in diameter class 3 was favored by the presence of smaller diameter logs compared to class 2, as smaller diameter wood is less resistant to heat transfer and the time for heat to reach the innermost regions of the wood tends to be shorter (Pereira et al., 2016).

Hygroscopic water exits the wood through diffusion, taking the shortest path, which means it traverses the wood cells until it reaches the surface. In this context, a larger log diameter increases the distance that water needs to travel, slowing down its exit from the wood and reducing the drying rate. It should be noted that all treatments were subjected to 68 hours of drying, regardless of the diameter class. The same trend was observed by Zanuncio et al.(2014), Oliveira et al. (2017), and Jesus et al. (2019).

4.3 Gravimetric yield and charcoal properties

The charcoal gravimetric yield, as well as the fixed carbon, volatile matter, and ash content obtained, are suitable for steelmaking applications (Pereira et al., 2013; Ramos et al., 2023). The values of impurities are close to those found by Ramos et al. (2023), and the fine particle content is in accordance with Damásio et al. (2015). This indicates that the integration of the furnace/boiler system with the dryer did not adversely affect the carbonization process. However, the bulk density did not reach the recommended value for charcoal use in the steel industry (Pereira et al.,2013), with values similar to those found by Donato et al. (2020). For use in the steel industry, a bulk density greater than 200 kg/m³ is recommended (Ramos et al., 2023).

The average friability was 10,8%, which is suitable for charcoal production and classified, according to CETEC, as a low friability charcoal (CETEC, 1982; Donato et al., 2020).

For carbonization in a rectangular masonry kiln, it is advisable that the amount of semicarbonized wood generated should be between 5% and 10% of the wood load volume. Thus, the percentage of partially carbonized wood generated in the carbonizations is within the acceptable limit (Ramos et al., 2023).

4.4 Drying energy balance and estimated charcoal yield gain

The thermal efficiency was higher in the drying process of logs with smaller diameters, suggesting that the heat energy provided for drying was better utilized for this class. Lower efficiency was observed for logs in Class 2, with larger diameters, indicating greater thermal losses in this process and also representing the greater difficulty in drying these logs. Jesus et al. (2019), in their study on the thermal decomposition of wood with different diameters and moisture content, observed that an increase of 1 cm in diameter increased the drying time by 13.5 minutes. These results corroborate the findings for the drying rate and moisture reduction, where smaller diameter woods dried more quickly compared to larger diameter woods, due to the greater resistance of larger diameter woods to heat transfer, as they consume more energy to remove water from the wood, from the center to the surface of the log.

The parameters obtained from intensive thermal energy and intensive electrical energy are important as they will serve as a basis for the design of the industrial dryer. With the obtained values and knowing the dry mass of wood that will be stacked in the dryer, it will be possible to estimate the amount of thermal energy required and also estimate the electrical energy consumption of the system in order to proceed with the drying process.

The energy demand for water removal from wood was directly proportional to the amount of water removed during the drying process. This was influenced not only by the log diameter class but also by the initial and final moisture content. The latter factor de-termined the proportion of bound water eliminated, as more energy is required to remove this type of water from the wood (Donato et al., 2020).

In the carbonization estimates, the average gravimetric yield was 32.4% (Table 5). Thus, it can be observed that there would be an additional gain of 4.9% in charcoal yield when using pre-dried wood in a metallic dryer. Extrapolating this result to an industrial production scale that uses 150 t of dried wood per kiln, the gain in charcoal could reach 2.3 t per batch.

Besides the increase in gravimetric yield of charcoal, the use of wood with low moisture content reduces the carbonization cycle because there is less water in the logs to be eliminated in the drying phase (Carneiro et. al., 2013; Ramos et al., 2023). Jesus et al. (2019) observed that higher moisture content causes larger endothermic peaks during wood carbonization due to the energy expenditure for water evaporation, which hinders charcoal formation and extends the total cycle time.

5. CONCLUSION

The kiln-furnace system coupled with a metallic dryer for energy recovery from carbonization gases proved to be effective in reducing wood moisture in all three classes and technically feasible for the artificial drying of wood, with an average reduction of 36.45% in its moisture contente, showing potential for large scale utilization.The gas temperature at the combustion chamber outlet was above 650°C. The mixing system reduced the gas temperature so that it entered the dryer at 159°C and exited at 81.09°C, temperatures low enough to reduce the wood moisture without promoting its degradation, resulting in an average moisture reduction of 36.45%. The electricity consumption per dry ton of wood was 49.4 kW. The thermal efficiency in reducing log moisture content was 0.61, 0.27, and 0.36 for logs in Class 1 (8 to 14 cm), Class 2 (14 to 22 cm), and Class 3 (8 to 22 cm), respectively. The intensive thermal energy found for Classes 1, 2, and 3 was 4707, 4558, and 5440 J/s per dry ton of wood, respectively. An estimated average gain of 4.85% in charcoal gravimetric yield was achieved with the drying method employed.

AUTHOR CONTRIBUTIONS

ACOC: Conceptualization, methodology, investigation, original draft preparation, writing. MTC: Writing. AJVZ: Writing, review, editing. EGP: Methodology, investigation, original draft preparation. AMMLC: Supervision, review. MAM: Methodology, investigation. DPSG: review, editing. ELCE: Writing, editing. VRC: Supervision, review, editing. AGC: Methodology, investigation, original draft preparation. SOA: Funding, review, editing.

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