Fuel 226 (2018) 508–515

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

# Thermal inertia effects of the structural elements in heat losses during the charcoal production in brick kilns

Jaime Daniel Bustos-Vanegas, Marcio Arêdes Martins*, Angélica de Cassia Oliveira Carneiro, Arthur Gomes Freitas, Ruben Christian Barbosa

*Universidade Federal de Viçosa, Viçosa 36570-900, Brazil*

ARTICLE INFO

*Keywords:*
Biomass
Heat transfer
Modeling
Simulation
CFD

ABSTRACT

Brazil is the largest producer of charcoal from planted forests with 5.5 million tons in 2016. The Brazilian steel industry consumes 85% of the national production of charcoal from eucalyptus. The walls and floor of industrial brick kilns are built using isolation materials that minimize heat losses during the wood carbonization stage. However, the thermal inertia of these components represents additional heat that must be removed during the charcoal cooling stage, as reflected in the extended process time. This study aims to evaluate the effect of the thermal inertia of the kiln structural elements for the charcoal production. A CFD (Computational Fluid Dynamics) analysis was performed to simulate the heating and cooling of the system composed of wood, carbonization gases, brick walls and floor. A typical industrial kiln with capacity of 700 $m^3$ was modeled and validated using a set of experimental measurements of temperatures during a 4-day carbonization stage with final temperature of 400 °C and an 8 day cooling stage. The temperature profile in the walls was linear, corresponding to a pseudo-steady state, where the thermal load increases with the pyrolysis time. The heat transfer at the floor is extensive; therefore, the adiabatic boundary condition cannot be imposed at the wood bed–floor interface. Our findings provide important information for the improvements in the kiln operation and allow establishment of consistent initial conditions of temperature and heat flux for kinetics models for charcoal cooling in kilns.

## 1. Introduction

Brazil is the largest producer and consumer of charcoal from planted forests, with production reaching 5.5 million tons in 2016 [1]. In terms of Brazil's market share, 85% of the production is destined for industrial use, mainly as a bio-reducer of iron ore in the pig iron and steel industries [1]. Charcoal is a renewable product with advantages over coal because of its higher carbon content, which contributes to the reduction of $CO_2$ emissions. However, the implicit production cost of charcoal is a limiting factor of its use.

In the current scenario, where global warming is a reality, production systems should be designed with consideration of not only economic gain but also, reducing environmental impacts. In the charcoal process, efforts are focused on the reduction of the emissions of pollutant gases via burning the outlet stream and extraction of the released energy [2,3] and on the process optimization, via reduction of the cooling time.

Charcoal production is based on a thermochemical process known as slow pyrolysis. The quality of the charcoal is a function of the wood quality and carbonization rate. The process occurs in four stages governed by the temperature: wood drying, up to 110 °C; roasting, up to 250 °C; carbonization, up to 350 °C; and carbon fixation, up to 450 °C [4,5]. After the last stage, the charcoal mass into the kiln should be cooled prior the discharge. The carbonization time in typical rectangular kilns, that varies between 190 and 700 $m^3$ of capacity is approximately 4 days, with the cooling time via natural convection of 9 and 14 days, respectively.

The carbonization process is performed in brick kilns. The bricks have insulating characteristics adequate for the carbonization phase, but unfavorable for the cooling, resulting in a long process time and therefore low productivity. Cooling the charcoal bed involves cooling the inner gases, the walls and even the floor of the kiln, which is usually composed of compacted clay. The thermal properties of those structural elements affect the overall heat transfer and needs to be well known.

Artificial cooling systems via forced heat convection have been developed by companies in an attempt to reduce the cooling time and consequently to increase the productivity [6,7]. Some prototypes using evaporative cooling have also been tested [8], although without

* Corresponding author.
*E-mail address:* aredes@ufv.br (M.A. Martins).

https://doi.org/10.1016/j.fuel.2018.04.024
Received 30 November 2017; Received in revised form 10 February 2018; Accepted 4 April 2018

**Nomenclature**

| | |
|---|---|
| $a$ | absorption coefficient |
| $l$ | characteristic length, m |
| $\gamma$ | charcoal emissivity |
| $C$ | constants in the turbulence model |
| $S$ | Coordinate along the path of radiation |
| $\rho$ | density kg/m$^3$ |
| $\varepsilon$ | dissipation rate of the turbulent kinetic energy, m$^2$/s$^2$ |
| $L_c$ | dome height, m |
| $\mu$ | dynamic viscosity, Pa s |
| $\sigma_\varepsilon$ | equivalent Prandtl number for dissipation of the turbulent kinetic energy |
| $\sigma_k$ | equivalent Prandtl number for the turbulent kinetic energy |
| $\beta$ | expansion coefficient, K$^{-1}$ |
| $h_{ext}$ | external heat transfer coefficient by convection, W/m$^2$ K |
| $\vec{V}$ | fluid velocity [(u, v, w)], m/s |
| $Gr$ | Grashof number |
| $g$ | gravity, m/s$^2$ |
| $A_s$ | interfacial area, m$^{-1}$ |
| $h_i$ | interfacial heat transfer coefficient, W/m$^2$ K |
| $\delta_{ij}$ | Kronecker delta |
| $\Phi$ | phase function for scattering |
| $d_p$ | pore diameter, m |
| $\varphi$ | porosity |
| $Pr$ | Prandtl number |
| $i$ | radiation intensity, W/m$^2$ |
| $Pk$ | rate production of the turbulent kinetic energy, Pa/s |
| $Ra$ | Rayleigh number |
| $\tau$ | Reynolds stress tensor |
| $\sigma_s$ | scattering coefficient |
| $\omega$ | solid angle |
| $C_p$ | Specific heat, J/kg K |
| $\sigma$ | Stefan-Boltzmann constant |
| $T$ | Temperature, K |
| $k$ | Thermal conductivity, W/m K |
| $t$ | time, s |
| $k^T$ | turbulent kinetic energy, m$^2$/s$^2$ |
| $L_w$ | wall height, m |
| $C_{pw}$ | wall specific heat, J/kg K |
| $T_w$ | wall temperature, K |
| $\lambda$ | wavelength |

*Subscripts*

| | |
|---|---|
| $b$ | Floor |
| $f$ | Fluid phase |
| $s$ | Solid phase |
| $t$ | turbulence |
| $w$ | Wall |
| $ef\text{-}s$ | effective thermal conductivity |
| $surf$ | external surface |
| $s\text{-}i$ | Internal surface |

thorough knowledge of the carbonization and cooling kinetics, thus limiting their implementation on an industrial scale.

Modeling and simulation are tools for use in analysis, design and project optimization. Some previous research focused on modeling the process of charcoal cooling and charcoal carbonization [8–10] with adoption of simplifications that sometimes do not consider physical phenomena of importance, e.g., time-dependent boundary conditions. Computational fluid dynamics (CFD) allows the evaluation of different scenarios and configurations of cooling and carbonization systems in simulated prototypes, saving both costs and time of experimentation.

This study is the first report in the literature of a mathematical model for simulation the carbonization in a rectangular brick kiln. The model was used to investigate the thermal inertia of the structural components and to provide information for formulation of mathematical models that include the heat transfer during the charcoal cooling.

## 2. Methodology

### 2.1. Experimental setup

The carbonization kiln under study corresponds to the industrial model 390 from Vallourec Florestal, with wood load capacity of 700 m$^3$, internal dimensions of 32 m in length, 4 m in width, 4 m in height, with a1.2 m high dome (Fig. 1). The walls are built with 0.24-m thick clay brick and doors at each end are constructed of concrete with a thin metal structure. Four chambers located below the kiln provide the energy required for ignition and for starting the pyrolysis. The ignition chambers are four structures located just below the floor surface (Fig. 1B) and equidistant throughout the kiln. In this chambers, wood is burnt at the beginning of the process (first 5 h of the carbonization stage). The gases resulting from this combustion process are conducted along the kiln by a channel located just below the floor (Fig. 1D). These hot gases circulate the bed of wood providing the energy for starting the pyrolysis. The two energy sources at the base of the wood bed (Fig. 1C) represents the energy provided for the combustion gases, which are responsible for the natural convection flow into the porous section and the gas head space over the bed. Its implementation into the model will be described further on.

The carbonization stage takes 4 days with a final temperature of 400 °C. The further cooling stage lasts for 8 days in natural convection condition with a final temperature of 50 °C. The carbonization gases flow through a duct to a central burner.

Three production cycles were monitored via a data acquisition system consisting of 17 J-type shielded thermocouples 4 AWG, three data acquisition modules (ICP CON 7018) and one interface module (ICP CON 7520) connected to a computer. At 1 m high, the thermocouples recorded the average of 11 measuring points of temperature of the inner wall face during the carbonization and cooling stages. At 3.8 m high, the average of 6 measuring points of temperature of the inner wall face were registered. The average temperatures recorded during the three cycles were used to validate the proposed model.

### 2.2. Model and simulation

The carbonization cycle was modeled to quantify the thermal effects of the thermo-chemical conversion of the wood bed to charcoal. It is important to remark that the focus of this work was not the modeling of pyrolysis reactions. Therefore, the overall heat generated by the wood drying and subsequent pyrolysis was modeled as an energy source in the heat transfer governing equations. This source was calculated based on a thermal balance and adjusted for typical values of reaction heat of pyrolysis in literature. A typical carbonization cycle of 12 days (4 days for the carbonization stage and 8 days for the cooling stage) was modeled and simulated with the CFD technique using ANSYS CFX v11.0 software.

#### 2.2.1. Physical model

The computational domain is defined by the kiln brick wall, the clay floor and the inner porous material (Fig. 1). Because the length of the kiln is significantly greater than its width, the heat transfer to the external environment occurs mainly in the cross-section. Thus, a two-dimensional approach can be performed, creating two solid subdomains