MODELING OF POROUS MEDIA IN A RECIPROCATING GRATE FURNACE OF A 3MW BOILER BURNING EUCALYPTUS CHIPS

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ABSTRACT: Reciprocating grate furnaces are widely used for burning solid fuels, including forest residues, wood chips, and sugarcane bagasse, among others. However, these grates are subjected to high oven temperatures, abrasion caused by the fuel, and corrosive substances produced during combustion, which can increase maintenance costs and decrease efficiency, as well as have negative environmental impacts. To address these challenges, recent studies have aimed at improving grate design and performance. In this work, we present a CRFD (Computational Reactive Fluid Dynamics) simulation of the grate and fuel bed as porous domains. The simulation was carried out using ANSYS-FLUENT, and the results show good agreement with the real geometry in terms of pressure and velocity. Our model provides valuable insights into the combustion reactions and the pressure drop generated by the grate inside the furnace, which can help to optimize the design and operation of these furnaces. The average furnace temperature obtained from the simulation is around 1000 °C, consistent with results reported by the boiler manufacturer.
Keywords: biomass combustion; moving bed furnace; reciprocating grates; CRFD simulation.

1 INTRODUCTION

The technological development of biomass steam-generating units is in line with growing concerns, such as the intensive use of fossil fuels and impacts resulting from greenhouse gases. Brazil is a world leader in the use of renewable energy, with biomass accounting for 9% of the country’s total electricity [1]. The goal is to reduce fuel consumption and greenhouse gas emissions, for that matter investing in the development of high-efficiency biomass technologies.

A biomass bed is essentially an agglomeration of solid particles, with a specific particle size, supported on a grate and bounded by the furnace walls. These particles are in contact with the surrounding particles, forming voids between them. When the bed is described by a computational mesh, the volume fraction of a cell occupied by the gas phase is described by the porosity of the bed [2].

The pressure drop in a biomass bed is correlated to the particles’ characteristics such as size, shape, and orientation. Thus, in addition to porosity, other parameters are needed to model particle systems with different shapes [3]. Biomass can be converted into thermal energy through direct combustion in steam generator furnaces, producing steam for electricity conversion.

Two technologies, fluidized bed and grate burning, stand out for the conversion of biomass in boiler furnaces. According to the technical information available in the literature, fluidized bed firing plants are designed with higher capacities. In the case of grate firing furnaces, the capacities are smaller, usually below 20 MWth [4]. In the other hand, according to Yin et al. [5], the capacities of grate-fired boilers range between 20 and 50 MWth. Specific cases even point to heat release rates of up to 4 $MWth/m^2$, depending on the characteristics of the biomass, such as high volatility and low ash content and the heterogeneous particle size of the fuel.

In medium and small boilers that use biomass as fuel, in the form of chips, most furnaces use reciprocating grates. The combustion process fundamentally depends on the elemental composition and moisture content of the fuel, in addition to the size, shape, and density of the particles distributed on the grate [6].

The Brazilian steam generator manufacturing industry designs boilers using empiricism-based methods [7]. Such methods require high investments for experimental investigation but can be improved using CRFD tools very quickly and dynamically and at a much lower cost. Such grates must be resistant to high temperatures, abrasion caused by fuel and attacks of corrosive substances produced during the combustion process.

In this context, CRFD simulation is an important tool that evaluates how combustion reactions occur within a discrete domain, generating solutions to manufacturing problems and modifications to increase the efficiency in furnace boiler [8].

The scientific innovation consists in solving the combustion problem considering both, the reciprocating grate and fuel bed, as porous media, taking as a basis data provided by the manufacturer, in this case focused on eucalyptus chips.

The aim of this work is to numerically analyze the biomass combustion process in a reciprocating grate furnace by modeling the bed and the grate as porous media. Considering CRFD (Computational Reactive Fluid Dynamics) simulation as an important tool to evaluate chemical reactions within a discrete domain, generating solutions to aid the grate manufacturing process, proposing modifications optimization and of this form attempting to increase the efficiency of this equipment. The pressure drops, temperature across the grate and biomass bed were investigated, viscous and inertial resistance coefficients were estimated based in methodologies available in the literature.

2 SIMULATION METHODOLOGY

2.1 Geometry of the reciprocating grate furnace

A 3 MW biomass-burning boiler makes up the system under investigation. The boiler is made up of a watertube furnace with a reciprocating grate. Two superheaters, which weren’t included in the simulation, exchange heat with the furnace's output at the boiler. Operational data for the equipment is shown in Table 1. Five air chambers under the grate distribute primary air. The primary air distribution along the grate can be prepared to provide the best fuel-air ratio for different sections of the fuel bed.

The reciprocating grate furnace used for this work is shown in Figure 1. The reciprocating grate comprises fixed and moving parts, in which fuel is transported along the grate by periodic alternating movements of the grate thus mixing unburned and burned fuel. The bars of grate are shown in Figure 2.

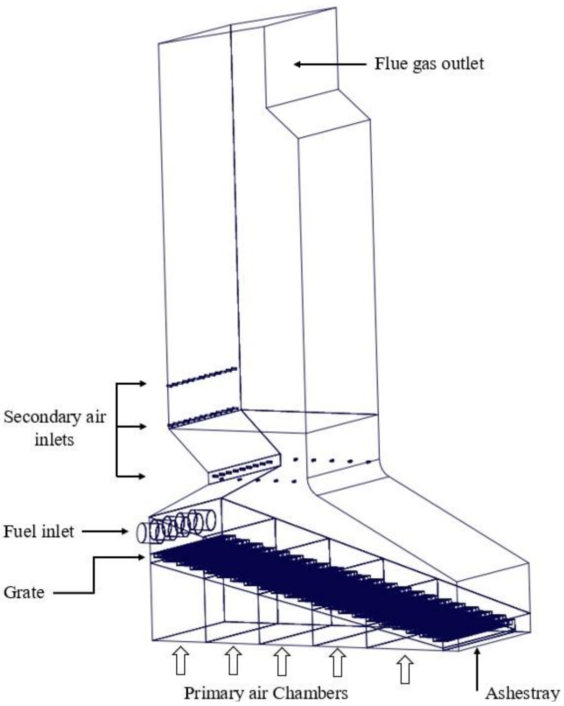

Figure 1: Geometric model of the furnace

The reciprocating grate is made up of 22 rows of moving grate bars. The furnace is 18 meters high, with a grate that is 4.5 meters wide by 10 meters long. The fuel is moved ahead and mixed as the rows advance.

Table I: Boiler operating parameters

Operating parameters	
Boiler load (MW)	3.0
Primary air, chamber 1 (kg/s)	1.53
Primary air, chamber 2 (kg/s)	4.60
Primary air, chamber 3 (kg/s)	4.60
Primary air, chamber 4 (kg/s)	2.44
Primary air, chamber 5 (kg/s)	2.14
Secondary air (kg/s)	6.54
Steam output pressure (bar)	43.10
Steam output temperature (°C)	420.40

The fuel bed is influenced by radiation from the flames and furnace walls, as well as the grate's movement and primary air supply. Fuel is fed from the top of the grate, while primary air is supplied through slots or holes between grate bars from below to the bed.

As shown in Figure 3, two ways of approaching the problem are presented. The first approach considers the fluid volume representing the furnace, comprising the primary air intake collectors, secondary air injectors, fuel inlet, grate, and biomass bed. This approach provides results regarding the temperature, species, velocities, and pressure profiles inside the furnace. However, the grate cannot be simulated with its actual geometry, due to the large number of geometric details of the reciprocating grate. Thus, the grate is represented as a porous medium.

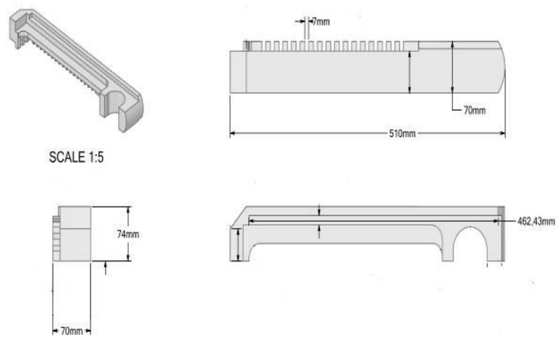

Figure 2: Grate bar geometry.

To do this modeling, a simulation is performed with two pairs of grates with the original grate geometry and then the data for pressure drop and velocities are used in a porous medium representative of the holes in the grate. Thus generating a second approach to the problem more specific to a few grate pairs that serve as boundary conditions for the furnace approach, thus reducing computational effort, leaving the simulation faster and requiring fewer computational resources. Thus having the possibility to verify the biomass degradation processes, the burning of volatiles, heat transfer, and modifications that can both improve efficiency and increase the lifetime of the equipment. memory capacity.

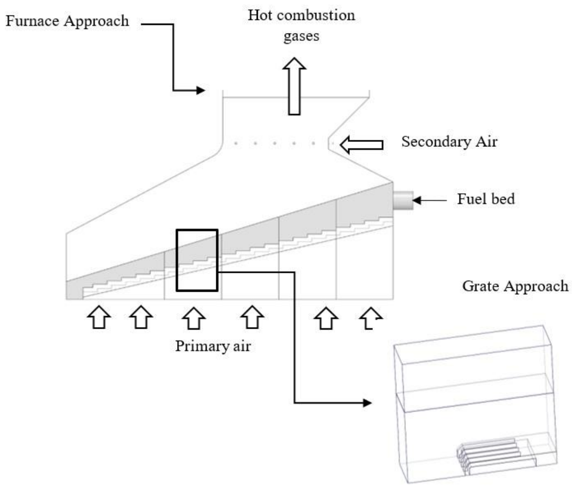

Figure 3: Simulation modeling approaches.

2.2 Mesh

The mesh was made for two approaches, the first represents the furnace as a whole and the second represents a portion of the grate bed composed of two pairs of grates as shown in Figures 4 and 5 respectively.

Tetrahedrons in three dimensions were employed as the surface elements during the ANSYS meshing process since Fluent Mesh was used to generate the mesh. When utilizing the inflation tool, the mesh is finer in regions where more gradients are anticipated, in volumes with three hexahedral layers on surfaces where the boundary layer occurs, such as close to walls, beds, grate, and secondary air injectors. The mesh created in the furnace was composed of polyhedral elements its size, about 1.8 mm and 60 mm, respectively, are the smallest and largest cell diameters and quality are shown in Table 2.

The mesh created for the grate approach was made with two models, the first considering the hole geometry and a second considering the holes as a porous medium. For the two models their size and quality can be seen in Tables 3 and 4 respectively. The cell size was the same for both hole models, maximum size of 6 mm and minimum of 0.81 mm. Despite this, the porous model has a much smaller number of elements, and its quality metric is also much higher. This translates into less computational effort and better convergence of the results. Mesh convergence studies were performed, but no major differences were obtained. Therefore, the smaller sizes were maintained due to the lower computational effort.

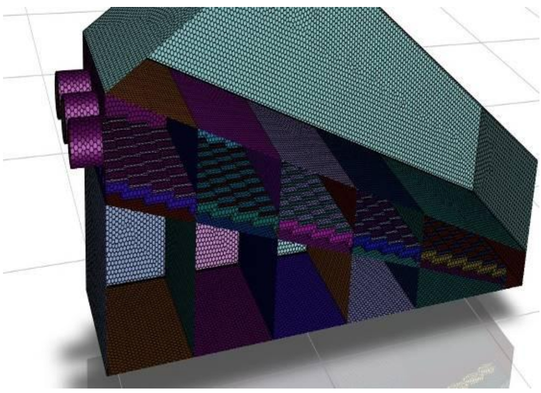

Figure 4: Furnace approach mesh

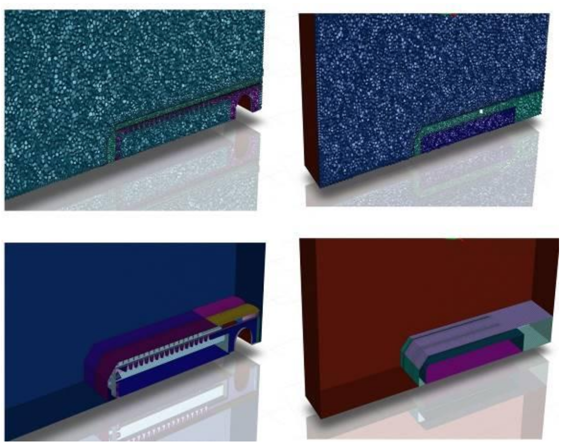

Figure 5: Mesh of the grate approach.

In terms of the mesh statistics, the skewness quality metric was used as the surface elements along the meshing process, and it is advised to select a low value it has a maximum value of 0.55 according to the skewness metric.

To solve the three-dimensional gas phase, the researchers applied the governing equations (Equations 1 through 4) using the finite volume method [3]. This numerical approach allowed them to discretize the domain into finite volumes and compute the fluxes across their boundaries, resulting in an accurate and efficient solution to the equations. All transport Equations were set up using the second order upwind technique.

$$\frac{\partial(\rho_g)}{\partial t} + \nabla(\rho_g u_g) = S_g \quad (1)$$

$$\frac{\partial(\phi\rho_g u_g)}{\partial t} + \nabla(\phi\rho_g u_g u_g) = -\phi\nabla p_g + \nabla(\phi\tau) + \phi\rho_g g - \beta_{g-s}(u_g - u_s) + f_g \quad (2)$$

$$\phi\rho_g C_{pg}\left(\frac{\partial T_g}{\partial t} + u_g\nabla T_g\right) = \nabla(\lambda_g\nabla T_g) + h_{g-s}(T_s - T_g) + \Delta H + \dot{Q}_{rad,g} \quad (3)$$

$$\frac{\partial(\phi\rho_g Y_{g,n})}{\partial t} + \nabla(\phi\rho_g u_g Y_{g,n}) = \nabla(\phi\rho_g D_{g,n}\nabla Y_{g,n}) + R_{g,n} \quad (4)$$

2.3 Thermo-chemical conversion of biomass

Biomass is mainly composed of cellulose 40-50% by weight, hemicellulose 25-35% by weight, and lignin 15-35% by weight [9]. The types of biomasses that can be used in furnaces with reciprocating grates are quite varied, with emphasis on wood chips and wood residues, among which can be mentioned eucalyptus and pine. The proximate analysis and ultimate analysis are shown in Tables 5 and 6.

Table II: Mesh furnace

Mesh Features	
Cells	1973503
Faces	11419044
Nodes	8494587
Maximum Aspect Ratio	68.67
Minimum Orthogonal Quality	0.18

Table III: Mesh real grate

Mesh Features	
Cells	1076050
Faces	6139037
Nodes	4536040
Maximum Aspect Ratio	226.42
Minimum Orthogonal Quality	0.008

Table IV: Mesh porous grate

Mesh Features	
Cells	572865
Faces	3383525
Nodes	2563685
Maximum Aspect Ratio	49.57
Minimum Orthogonal Quality	0.109

The thermochemical conversion of solid fuels, such as biomass, is a complex process and involves a series of very distinct steps. These correspond to drying, pyrolysis, coal gasification, coal oxidation, and ash formation. For each sub-process models are needed that are added as source terms in the equations that are used by simulation programs. [10]. For the biomass bed, these processes occur sequentially, however, analyzing only one particle, it can be considered that they occur simultaneously in large particles that present large thermal gradients.

The moisture content in the biomass is a factor that influences the behavior of the furnace, as it impacts parameters such as the combustion temperature and the volume of gases emitted. Woods with high moisture content present some difficulty for burning, as they consume large amounts of energy and have longer drying times, with devolatilization and coal combustion occurring later [3]. The drying process, which requires energy consumption for the evaporation of the water that is contained in the biomass bed, occurs at temperatures ranging from 60°C to 100°C. Drying can occur in two ways: by diffusion, when it occurs below the boiling point, and by evaporation, when it reaches the boiling point.

Table V: Proximate analysis.

Proximate analysis	
Moisture (wt%)	33.75
Volatile (wt%)	57.54
Fixed carbon (wt%)	8.3
Ash (wt%)	0.41
LHV (MJ/kg)	9.48

Table VI: Ultimate analysis

Ultimate analysis (dry basis), wt.%	
C	47.87
H	8.08
N	0.02
S	0.03
S	43.38

Biomasses in general release a large portion of volatile matter, consisting of tar and low molecular weight gases. Dry wood is thermally decomposed in the temperature range of 150°C to 350°C. The pyrolysis process prevents oxygen from penetrating the fuel due to the outflow of released gases. Thus, no heterogeneous reaction of the solid part is possible [3]. Devolatilization is also called pyrolysis and is an endothermic process of biomass degradation. It is a function of factors such as heat transfer rate, temperature, composition, and type of biomass. The volatiles released by the fuel bed are burned in the freeboard, forming the flame, and exchanging heat with the bed itself.

After the volatiles escape from the particles, only the char, which is assumed to consist of pure carbon and ash, remains in the solid product. Initially, the products of char combustion are CO and CO_2, depending on whether it undergoes partial or total oxidation [3]. This step occurs slowly, releasing a lot of energy at specific points closer to the combustion region. The burning of char occurs at temperatures above 600°C, and can reach values around 1000°C. Subsequently, char gasification, which occurs at temperatures above 800°C, produces larger amounts of carbon monoxide and hydrogen. After gasification, oxygen reacts with the fixed carbon to promote its complete oxidation. This heterogeneous and exothermic reaction generates carbon monoxide and carbon dioxide, leaving only the ash [2].

The thermal properties and porosity of the biomass bed experience changes as the biomass undergoes this sequence of thermochemical processes, so the modeling of the bed needs to be performed considering these changes in each grate section.

2.4 Combustion model

The combustion model used in the simulations was the EDM/FR (Eddy Dissipation/Finite Rate Model), in which the reaction rate is defined by the turbulence time scale or Arrhenius kinetics rate. The model gives a simpler and faster response based on species transport. The kinetics mechanism adopted was the one developed by [11]. This is a global mechanism to describe the oxidation of light hydrocarbons CH_4 as well as the complete oxidation of carbon monoxide and hydrogen. This improves the accuracy of the simulation since it operates with sets of reactions instead of just one reaction. The chemical reactions considered are presented in Equations 5 to 8.

$$2CH_4 + O_2 \xrightarrow{k_{g,1}} 2CO + 4H_2O \quad (5)$$

$$CH_4 + H_2O \xrightarrow{k_{g,2}} CO + 3H_2 \quad (6)$$

$$CO + H_2O \xrightarrow{k_{g,3}} CO_2 + H_2 \quad (7)$$

$$2H_2 + O_2 \xrightarrow{k_{g,4}} 2H_2O \quad (8)$$

The analysis considered seven chemical species: H_2O, CH_4, H_2, CO, CO_2, O_2, and N_2. To calculate the total gas flow that enters the freeboard for each zone, Equation 9 is used.

$$\dot{m}_{g,j} = \dot{m}_{H_2Os,j} + \dot{m}_{\text{Volatile}\, s,j} + \dot{m}_{COs,j} + \dot{m}_{CO_2s,j} + \dot{m}_{O_2s,j} + \dot{m}_{N_2s,j} \quad (9)$$

The total gas flow from the biomass bed is represented by $m_{a,j}$, where j is the corresponding zone and the subscripted letters account for drying, devolatilization, and gasification, respectively.

Equation 10 defines the mass fraction of each component in the gas mixture, where i represents the corresponding species.

$$\cdot Y_{i,j} = \frac{\dot{m}_{i,j}}{\dot{m}_{g,j}} \quad (10)$$

The mass flow associated with the biomass decomposition process in the j zone of the bed is given by Equation 11.

$$\dot{m}_{i,j} = \dot{m}_f \varphi_{i,j} Y_{i,j} \quad (11)$$

where $\dot{m}_f$ is the fuel feed rate, $Y_{i,j}$ is the mass fraction of it component of the biomass and $\varphi_{i,j}$ is the reaction rate in zone j.

Given the short residence times and insufficient mixing with oxygen, it can be assumed that combustion of gases within the fuel bed is negligible. Based on this assumption, the mass flow rate of volatile matter entering the freeboard can be estimated in a similar manner as Equation 11.

Tu et al. [11] simplified volatile matter into a single artificial species with a molar mass of 30 kg/kmol and used a simple decomposition reaction to calculate the mass flow rates of individual species (CH_4, H_2, H_2O, CO, and CO_2) during the devolatilization process.

In order to estimate the release of carbon monoxide and carbon dioxide resulting from char oxidation in the it zone of the fuel bed, Equations 12 and 13 are employed. These equations allow for the calculation of the mass flow rates of CO and CO_2, taking into account factors such as the rate of reaction, the temperature gradient within the zone, and the concentration of carbon in the char.

$$\dot{m}_{CO,j} = \dot{m}_f \varphi_{i,j} \left(\frac{28}{12}\right) \left(\frac{2500 \exp\left(-\frac{6240}{T_s}\right)}{1 + 2500 \exp\left(-\frac{6240}{T_s}\right)} \right) \tag{12}$$

$$\dot{m}_{CO_2,j} = \dot{m}_f \varphi_{i,j} \left(\frac{44}{12}\right) \left(\frac{1}{1 + 2500 \exp\left(-\frac{6240}{T_s}\right)} \right) \tag{13}$$

The CO/CO_2 ratio is calculated based on the temperature of the biomass bed (T_s). Finally, Equation 14 is used to calculate the amount of oxygen that leave the bed unreacted.

$$\dot{m}_{O_2,j} = \dot{m}_{PA,j} Y_{O_2} - \left(\frac{16}{28}\right) \dot{m}_{CO,j} + \left(\frac{32}{44}\right) \dot{m}_{CO_2,j} \tag{14}$$

To calculate the temperature of the gases entering the zones, the conservation of energy Equation 15 was used. The specific heat of the gas mixture, was calculated by Equation 16.

$$T_{g,j} = \frac{1}{\dot{m}_{g,j} \times C_{P_{g,j}}} \left(\dot{Q}_{rad,j} + \frac{12}{28} \dot{m}_{Co\,g,j} \dot{Q}_{O,p} + \frac{12}{44} \dot{m}_{Co_2\,g,j} \dot{Q}_{O,c} \right) - \frac{1}{\dot{m}_{g,j} \times C_{P_{g,j}}} \left(\dot{m}_{H_2O\,g,j} \dot{Q}_{evap} + \dot{m}_{vol\,g,j} \dot{Q}_{dev} \right) + T_{PA} \tag{15}$$

$$C_{Pg,j} = \sum_i \left(Y_{O_2} \times C_{Pi,j} \right) \tag{16}$$

The equation incorporates various terms, each of which represents a crucial aspect of the combustion process. $Q_{rad,j}$ denotes the net radiative heat transfer rate, while $Q_{o,p}$ (9208 kJ/kg) and $Q_{o,c}$ (32794 kJ/kg) correspond to the energy released during partial and complete carbon oxidation, respectively. Q_{evap} (2258 kJ/kg) represents the latent heat of vaporization of water, and Q_{desv} (418 kJ/kg) indicates the heat absorbed during the devolatilization of wood chips. Finally, T_{pa} refers to the temperature at which primary air is supplied to the combustion chamber, playing a critical role in the overall combustion process [11].

2.5 Porous medium

The combustion of biomass in a furnace involves the flow of air through a large number of small holes in the grate, which can lead to significant computational challenges during simulation. In the present study, each of the approximately 750 grate pairs in the furnace comprises 20 holes, resulting in a total of 15,000 holes. This concentration of mesh elements can result in high memory consumption and computational effort if the complete furnace is recreated using the actual grate geometry.

The combustion of biomass is a complex thermochemical process that involves the transformation of fuel properties as it progresses from a moisture-rich state to fixed carbon and ash. This process can cause significant changes in the porosity, specific heat, specific mass, and thermal conductivity of the fuel.

Since the impact on the pressure drop caused by the grate and the biomass bed cannot be disregarded, the following approach was used in this study.

To confirm the viscous and inertial resistance coefficients, a preliminary simulation was run with two pairs of grates with their actual geometries. To do this, a numerical experiment was conducted in which the coefficients of a pair of grate elements' pressure drop and velocities were evaluated using the Darcy-Forchheimer formulation, Equations 17 and 18.

The viscous and inertial resistance coefficients obtained will be employed in the furnace simulation to treat the entire grate as a porous media. The properties of the grate and bed are shown in the Table7.

Table VII: Grate and bed properties.

Biomass bed	Porosity, ε [-]	0.42
Grate	Specific mass [kg/m³]	7300
	Conductivity, λ [W/m·K]	30
	Specific heat, Cp [J/kg·K]	500

Source [2]

To calculate the coefficients of the Darcy-Forchheimer Equations 17 and 18, a table is assembled with flow, velocity and pressure data, the velocity curve is plotted against pressure and from the method of least squares an equation of the curve is generated. A simulation was performed with realistic grate geometry. A total of ten simulations were carried out, varying the mass flow from 0.01 to 0.1 kg/s and removing pressure drop values from the components of the velocity vector *u*, *v* and *w* in order to assemble the graphs in Figures 6 to 8.

The coefficients for porous medium modeling of the biomass bed were calculated and are shown in Table 8.

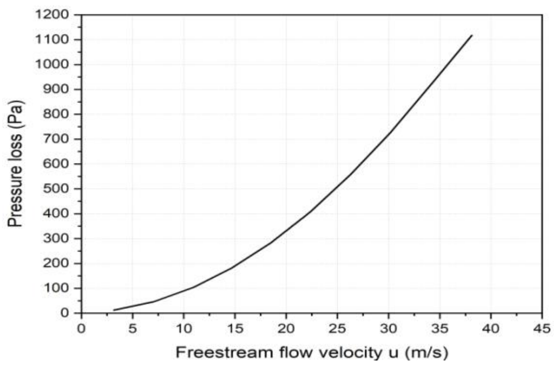

Figure 6: Pressure drop as a function of velocity *u*.

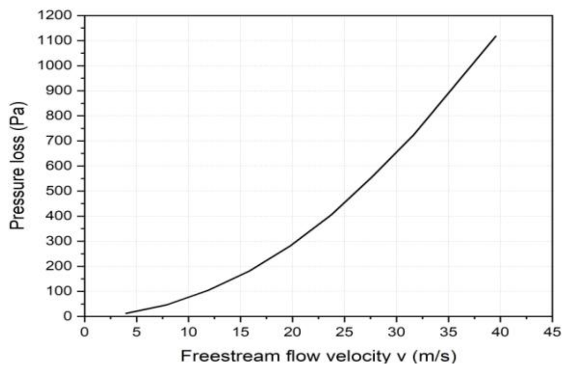

Figure 7: Pressure drop as a function of velocity *v*.

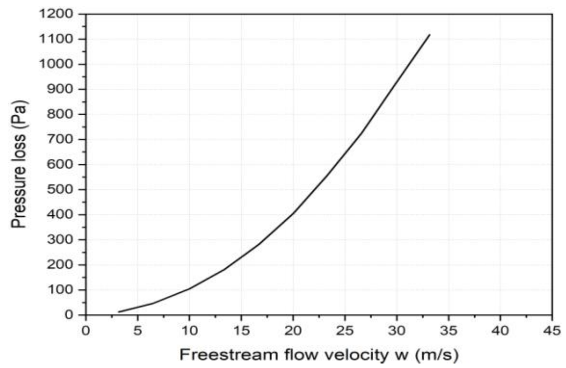

Figure 8: Pressure drop as a function of velocity *w*.

Table VIII: Pressure drop data for the bed.

	Viscous resistance [1/m^2]	Inertial resistance [1/m]
Wood	1702704.89	1369.99
Char	3160829.24	1245.60
Ash	1158404.12	586.92

To verify that the calculated coefficients for viscous and inertial resistance can be used in the simulations, a comparison was made of the velocity and pressure profiles between the grate with realistic geometry and grate with the holes represented as a porous medium.

For the biomass bed, a porous medium composed of several particles was considered, which can be modeled as a packed bed. The pressure drop in a biomass bed is related to the characteristics of the particles, such as size, shape, and orientation.

Thus, in addition to porosity, other parameters are needed to model particle systems with different shapes [3]. The pressure drops along a biomass bed, calculated by Ergun's expression Equation 19 and the correlation coefficients with fluid velocity. This equation is applied to a wide range of Reynolds numbers.

$$C_2 = \frac{3.5}{D_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{17}$$

$$\frac{1}{\alpha} = \frac{150}{D_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{18}$$

For the biomass bed, a porous medium composed of several spherical particles was considered. Based on the drag calculation. The particle diameter and bed porosity were taken from the work of [12]. Table 8 shows the initial porosity of the biomass and ash bed, as well as the grate properties that are used in the configuration of the materials in each zone.

$$\frac{\Delta P}{L} = \frac{1}{2}\rho C_2 v_s^2 + \mu\frac{1}{\alpha}v_s \tag{19}$$

3 RESULTS

The calculated coefficients for the estimated viscous and inertial resistance were used in the simulation. Figures 9 and 10 show the velocity and pressure profile on the grate domain respectively.

Both the pressure drop generated by the holes, as well as the average and maximum velocities show a good agreement with the values available in the grate technical literature.

To verify whether the calculated coefficients for viscous and inertial resistance can be used in the simulations, a comparison was made of the velocity and pressure profiles between the grate with real geometry 9a and 10a and the grate as a porous block 9b and 10b.

One can see very close values for the pressure in Figures. Inside the domain, the highest pressure was estimated around 460 Pa for both cases.

Regarding velocity, similar scales can be seen in. It is worth noting that the velocity distributions are not identical, but a valid simplification to decrease the computational effort of the furnace simulation in the first approach.

The velocity in the grate geometry, Figure 9a, has a larger variation due to the shape of the holes in the form of a convergent nozzle. Faster gas flow through the passages results in higher heat transfer coefficients, thereby increasing grate cooling.

The local combustion rate increases with gas velocity, also increasing the fuel cooling effect and heat dispersion. On the other hand, the mass transfer coefficient increases with gas velocity, which creates limiting rates for char combustion [12].

The overall effect of gas velocity on grate temperature is difficult to quantify due to many conflicting phenomena [12].

Figures 11 and 12 show the pressure and velocity variations for an average line through the grate holes. For the pore velocities, compared the velocities of the porous medium and the grate were left with a very small difference. Regarding the pressure it can be noted that the porous medium represents very well the holes of the grate

Figure 13 shows the temperature profile inside the furnace and Figure 14 shows the temperature profile in exit of furnace. The bed temperature varies according to the zone, staying in the range of 600 ºC to 950 ºC.

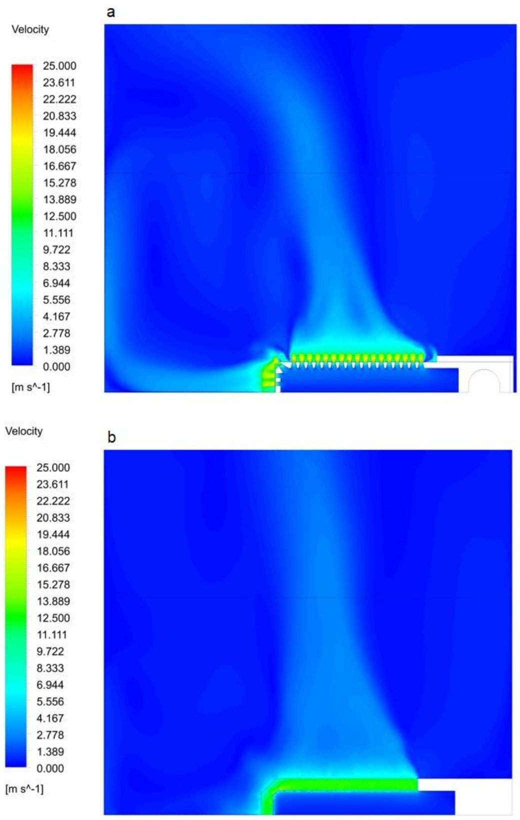

Figure 9: Velocity variation in grate approach

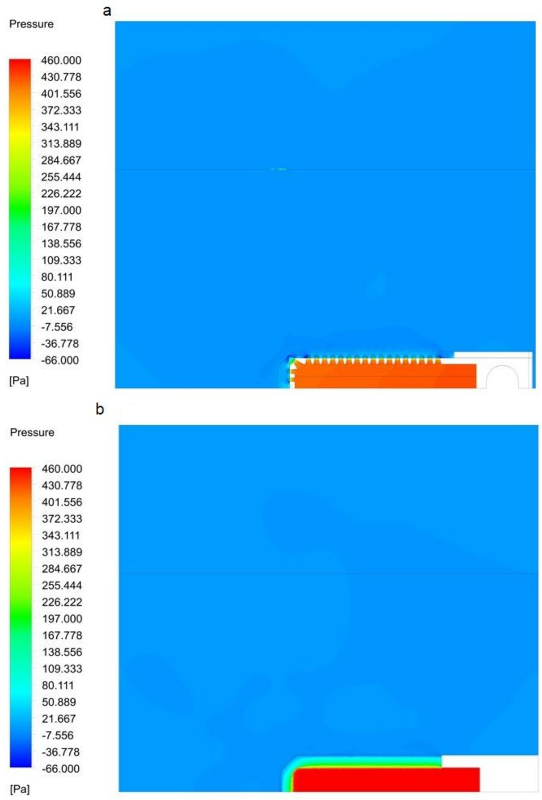

Figure 10: Pressure variation

In the drying zone lower values are found, while in the pyrolysis and carbon oxidation zones the temperatures are higher, due to the heat transfer processes coming from the volatile flame. About 70% of the combustion air is supplied to the bed to sustain the pyrolysis, char formation, gasification, and coal oxidation processes.

In the drying zone lower values of temperature are found, while in the pyrolysis and carbon oxidation zones the temperatures are higher, due to the heat transfer processes coming from the volatile flame.

The average temperature in the furnace is around 1000 °C and the highest temperature found was about 1500 ºC, concentrated in the secondary air intake region. The results presented good agreement with data provided by the steam generator unit manufacturer the furnace. The exit temperature from the furnace was measured at 856°C, while the simulation resulted in a temperature of 831°C.

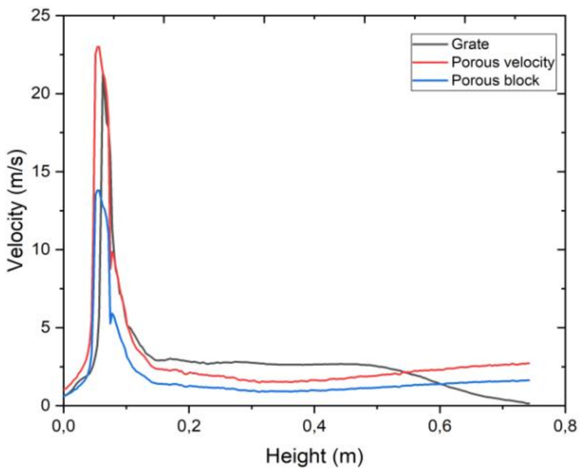

Figure 11: Velocity variation as a function of height in the grate approach

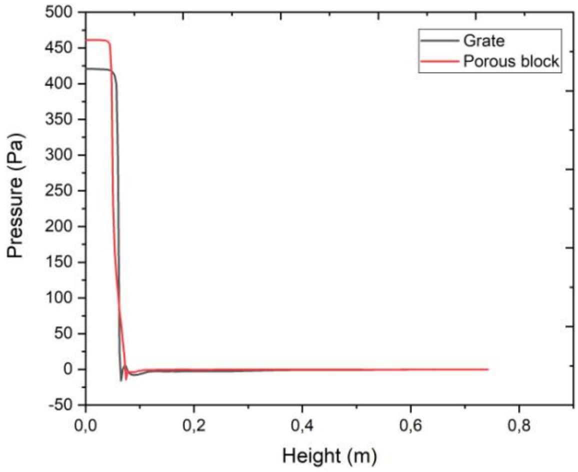

Figure 12: Pressure variation as a function of height in the grate approach.

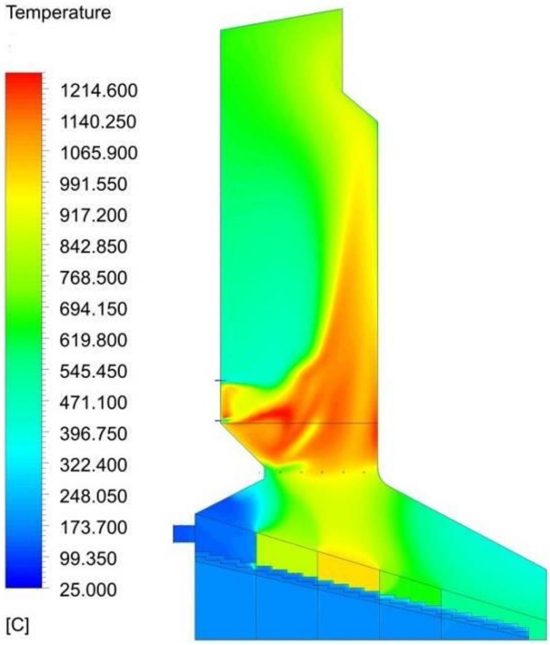

Figure 13: Temperature distribution in the furnace

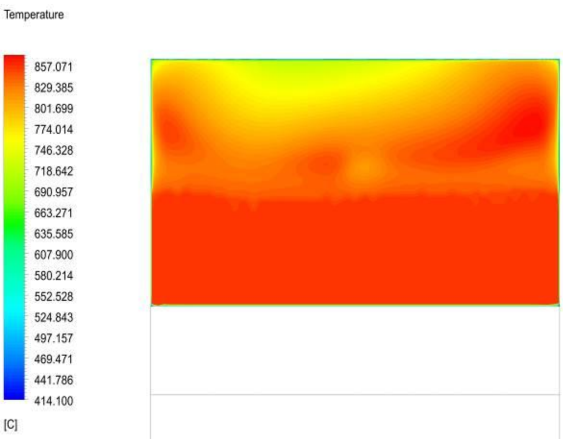

Figure 14: Furnace outlet temperature.

In Figure 15, the DO irradiation highlights that the majority of radiation penetrating the biomass bed is focused on the drying, pyrolysis, and gasification zones. This is essential since these zones necessitate a substantial energy input to facilitate the biomass's pyrolysis, drying, and gasification processes. Due to their endothermic nature, these stages of bed degradation absorb a significant amount of energy.

The obtained results can be compared with the values reported in the work of [13], which simulated a 13 MWth reciprocating grate boiler burning wood. Relatively high flue gas temperatures are found in the upper front section of the primary combustion domain.

The utilization of fuel in the grate firing furnaces ensures a consistent heat source for the raw feedstock, promoting efficient heating and drying in the early zones of the grate. However, elevated temperatures can cause deposition problems on the upper walls. It is worth noting that gas velocities in these furnaces are generally lower than those in suspension fired boilers. Inadequate design of the secondary air jets in the freeboard can result in a channeling effect, characterized by a fuel-rich, high-velocity flow in the center, surrounded by a low-velocity, oxygen-rich flow near the walls.

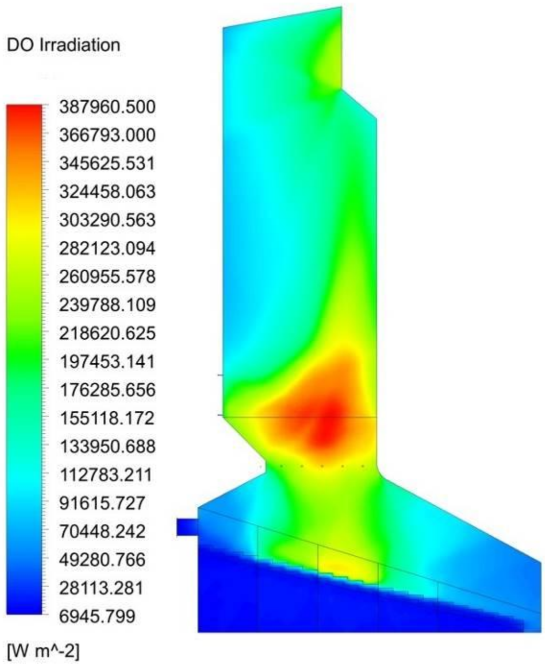

Figure 15: DO irradiation.

Figures 16 and 17 show, respectively, streamlines, turbulent kinetic energy, and velocity distribution in the furnace. Figure 16 clearly shows a recirculation region that is formed due to the secondary air intake. The points where the turbulent kinetic energy is highest are the same points that had the highest temperatures in the simulation.

This turbulence promotes greater mixing between the reactants, improving combustion efficiency. The highest velocity is around 46 m/s and occurs in the throat, near the secondary air inlets. One can see more uniform current lines for the porous regions. In these domains, the velocity is generally below 11 m/s.

Figures 18 show the variation of species in relation to the height of the furnace. One can compare the data with data provided by the manufacturers, showing that the results obtained in the simulation are in accordance with the operational data. The combustion gases will typically contain carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2), with the CO concentration being higher due to incomplete combustion.

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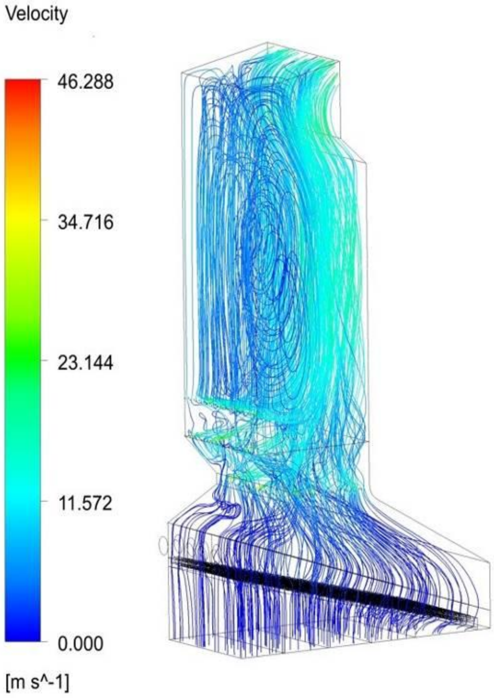

Figure 16: Streamlines.

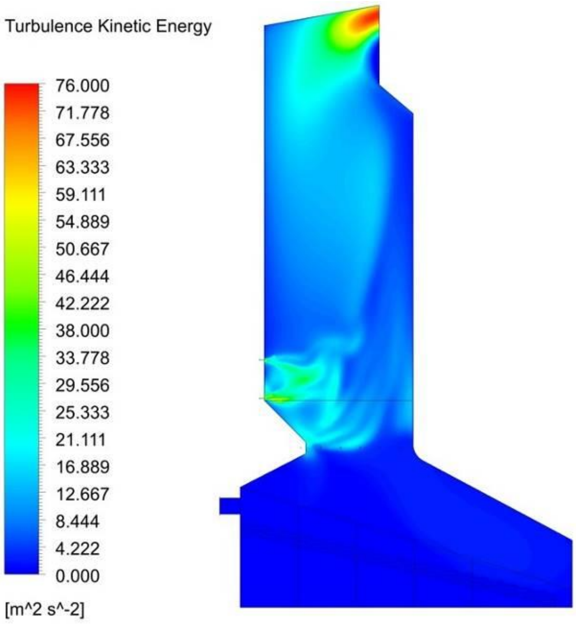

Figure 17: Turbulent kinetic energy.

Biomass combustion is a renewable and sustainable alternative to fossil fuel combustion, offering potential reductions in greenhouse gas emissions. Unlike fossil fuels, biomass is a renewable resource that can be produced locally, reducing transportation-related emissions. However, to ensure efficient and clean combustion, it is crucial to monitor and control the flue gases exiting a biomass furnace. By optimizing combustion conditions, such as temperature, oxygen levels, and residence time, and controlling gas species, biomass combustion can play a crucial role in a sustainable energy strategy.

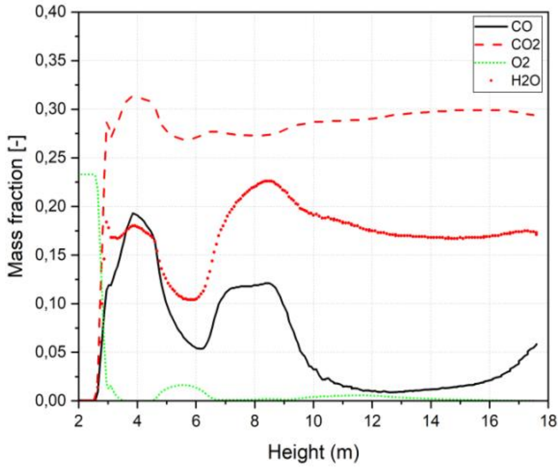

Figure 18: Species in relation to furnace height.

4 CONCLUSIONS

The proposed simulation approach for the reciprocating grate furnace proved effective in solving technological problems with low computational effort. The modeling of the fuel bed and grate showed good agreement with the technical literature, with values obtained for pressure and velocity aligning well with those of the real geometry.

The porous medium representation accurately described the pressure drop generated by the grate inside the furnace. The simulation results presented good agreement with data provided by the steam generator unit manufacturer and the technical literature in the area, with an average furnace temperature around 1000 °C and a maximum temperature of about 1500 °C concentrated in the secondary air intake region.

DO irradiation highlighted the need for a significant energy input in the drying, pyrolysis, and gasification zones, which absorbed much of the energy due to their endothermic nature.

The velocity distribution showed a recirculation region formed by the secondary air intake, promoting greater mixing between the reactants and improving combustion efficiency. The highest velocity of around 70 m/s occurred in the throat near the secondary air inlets, while the porous regions generally had a velocity below 11 m/s.

Species variation in relation to the height of the furnace also showed good agreement with operational data provided by the manufacturers. the simulation are in accordance with the operational data.

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