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# A REVIEW OF NUMERICAL MODELLING OF BIOMASS COMBUSTION IN GRATE-FIRED BOILERS

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***Abstract.*** *CFD is a tool that has been widely used for the design and solution of specific problems in steam generators due to its versatility and lower costs when compared to measurements and experiments; it reduces solution times and allows the visualization of temperature, flow and species fields in the simulation of a variety of flow conditions and types of fuels. The objective of this work is to present a literature overview of different results obtained from CFD simulations of grate-fired furnaces, reviewing its application in the development of boilers, such as in the investigation of primary pollutant emissions, deposit formation and corrosion. In most of the gathered data, a commercial software was coupled with specific mathematical models for the solid fuel conversion phases, i.e. drying, pyrolysis and char oxidation, and the models were validated with experimental measurements from operating equipment. These methodologies are shown to be a fundamental tool in increasing thermal efficiency and reducing the environmental impact of such technologies.*

***Keywords:*** *CFD, Combustion, Biomass, Grate, Boilers*

## 1. INTRODUCTION

Due to the increase in global warming, biomass fuels have been one of the main alternatives to coal combustion, by virtue of it being a sustainable source of energy, as, in many cases, $CO_2$ emissions are almost totally absorbed during the growth process of energy crops. Aiming power generation, space or process heating, a steam generator is a thermal equipment that delivers steam or hot fluid to the end use point at the desired pressure and temperature, whose source of heat, in most cases, is the combustion process of solid, liquid or gaseous fuels. Biomass-fired furnaces are generally classified in grate or fluidized bed systems; both have the flexibility of employing different types of solid fuels, including mixtures with coal (Yin et al., 2008).

According to Barroso et al. (2019), maintenance of high efficiencies with variable loads and fuel properties, e.g. the fuel moisture content, is one of the main targets of improvement during the development of boilers; but the phenomenology of combustion occurring inside this equipment is very complex and includes various phases, such as drying, vaporization, pyrolysis and gasification, and its understanding requires a deep knowledge of both fluid dynamics and chemical reactions. One of the tools used for the design and troubleshooting of steam generators is the Computational Fluid Dynamics (CFD), a science that produces quantitative predictions of fluid-flow phenomena using numerical approaches based on the conservation laws (conservation of mass, momentum and energy) governing fluid motion (Kundu et al., 2012). In this sense, CFD is a powerful tool for providing visual and quantitative output of the process performance, including flow and temperature distribution, pressure drop, species concentrations and mixing patterns, flame shape and wall heat fluxes (Singh et al., 2008).

There are many studies that deal with problems in coal steam generators using CFD tools, such as the work of Reinaldo et al. (2005), which took into account radiation and convection heat transfers and thermal gradients of the gases at the exit of the combustion chamber in order to predict the superheater wall temperature in pulverized coal steam generators. Another key issue that is often evaluated is light ash deposition, as they act like a thermal insulator in superheating surfaces, reducing heat exchanges and the thermal efficiency of the equipment. In the work of Mendes and Bazzo (2012), a porous structure was employed to analyze the growth of ash deposits in superheater tubes of coal-fired steam generators. Subsequently, Mendes et al. (2017) modeled a porous medium that represents the growth of an ash deposit and correlated it with the effective thermal conductivity, obtaining good agreement with measurements; the authors were, then, able to estimate the decreased heat exchange and increased wall temperature due to deposits of ash in the superheaters of steam generators.

Although many numerical studies on coal-fired steam generators are available in the literature, there are still few works that deal with the same problems in reciprocating grate furnaces employing biomass as fuel. The objective of this work is to present a review of the different results obtained from CFD simulations in the development of grate boiler furnaces, clearly showing its benefits, such as the reduction of design times and costs associated with experimental setups during the investigation of primary pollutant emissions, deposit formation and corrosion. The results of the review presented here are important in understanding the physical phenomena that occur in reciprocating grates, which will serve as a basis for current and future work at LabCET, in cooperation with steam generators suppliers.

## 2. MODELLING AND CFD SIMULATION

Grate furnaces are one of the most employed technologies in the conversion of biomass for years, burning a variety of fuels with different moisture contents; however, there are still some specific problems to be solved, such as corrosion, pollutant emissions, deposit formation and poor mixing in both the fuel bed and the freeboard (Yin et al., 2008). The combustion process of solid fuels occurs in a series of steps (drying, pyrolysis and char oxidation) and its simulation must consider models that combine the reactions at the solid-gas interface and the gas phase domain. Commercial software can solve the combustion in the gas phase, although they are still limited in the solid interactions with the oxidant gases through heat, mass, and species transfer (Karim et al., 2020).

The CFD simulation assesses how combustion reactions occur within the discretized spatial grid and enables, then, the solution of manufacturing problems and modifications to increase those equipment efficiencies. An important part of this optimization process is the validation of the employed numerical models, that must have close connections with real operational furnaces through measurements or empirical data.

## 3. LITERATURE OVERVIEW

The mechanisms of pollutant formation, ash deposition and corrosion during biomass combustion can all be traced to some extent to the corresponding mechanistic study in coal combustion and, partly because of this, research activities in this area are advancing in fast pace. However, biomass fuels fall over a very broad range, which not only result in different combustion characteristics but also cause some specific practical problems in operational plants (Yin et al., 2008). Currently, authors seem to be focusing on some key issues: primary pollutant emissions and control, deposit formation, corrosion and design troubleshooting. Because experimental works are expensive and difficult to be conducted, many Computational Fluid Dynamics efforts have been made to address these topics. In this sense, the objective of this section is to comprehensively look at the state-of-the-art with respect to biomass thermochemical conversion, highlighting studies in packed bed grate combustors.

Three different approaches on how to model the fuel bed can be found in literature. The first one integrates the bed and overbed in a single computational domain, treating the process of solid fuel conversion as a reacting porous zone. This approach can be entirely modeled within commercial software along with gas-phase reactions in the freeboard, usually needing the implementation of User Defined Functions (UDFs). In the second approach, more prevalent in the analysis of biomass-fired grate steam generators, reaction rates are prescribed as a function of the position on the grate. It is then possible to calculate the temperature, velocity and species concentration of the gases entering the overbed through the mass and heat balances of the fuel components and primary air (equilibrium calculation method). Subsequently, freeboard modelling uses this information as inlet conditions for the gas-phase simulation. Lastly, the third approach is the development of separate bed models, which simulates the biomass conversion on the grate in independent in-house codes (Rahdar et al., 2019). In short, these studies solve the mass, momentum, energy and species conservation equations for both gas and solid phases, with necessary process rate equations and empirical correlations used for the closure of the balances. In this way, the bed model provides the inlet conditions for the overbed simulation, whilst the freeboard simulation returns the heat flux released from the flame and furnace walls onto the fuel layer to the bed model. This modelling concept can be better understood in Fig. 1.

Among authors who followed the third approach, one may find considerable inconsistencies in the set of equations solved in different bed models; it is not uncommon to see the inclusion or neglection of some terms, depending upon the application studied. Differences in divergence operators or even in the inclusion of some transport equations, such as momentum equations, can be found. Table 1 exemplifies these variations, presenting the sub-processes and conservation equations included in selected works in which separate bed models were developed.

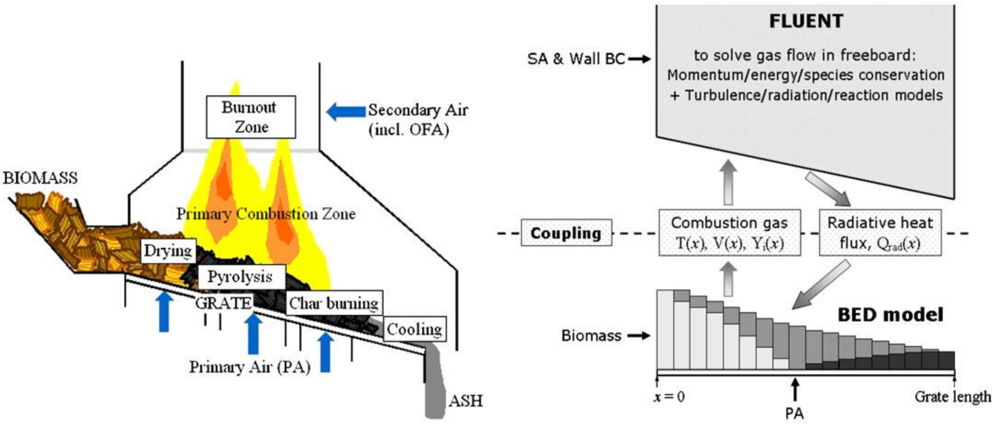


Figure 1. Grate firing of biomass: CFD and bed model coupling (Yin et al., 2008).

Concerning the gas phase combustion in the freeboard, commercial CFD codes built-in algorithms have been extensively developed in order to solve mass, momentum, energy, turbulence and species conservation equations. Due to this, authors can choose from many modelling methods. Table 2 organizes the different models employed in studies that address this topic.

Table 1. Sub-processes and conservation equations included in the bed model of selected studies.

| Ref. | Sub-processes | | | Conservation equations | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Drying | Pyrolysis | Char oxidation | Mass gas | Species gas | Energy gas | Momentum gas | Mass solid | Species solid | Energy solid | Momentum solid |
| 14 | | x | x | x | x | x | x | x | | x | |
| 16 | x | x | x | x | x | x | | x | x | x | |
| 18 | x | x | x | x | x | x | x | x | x | x | x |
| 17 | x | x | x | x | x | x | x | x | x | x | x |
| 21 | x | x | x | x | | x | | x | | x | |
| 12 | | x | | x | x | x | x | x | | x | |
| 25 | x | x | x | x | x | x | x | | | x | |
| 24 | x | x | x | x | x | x | x | x | x | x | |
| 22 | x | x | x | x | x | x | x | x | x | x | |

Adapted from Rahdar et al, 2019

Table 2. Models employed in the overbed gas phase combustion in selected studies (1)

| Ref. | Turbulence | Enhanced wall treatment | Chemistry/turbulence interaction | Thermal radiation | Gas phase absorption coefficient | Pressure/velocity coupling |
|---|---|---|---|---|---|---|
| 1 | k-ε | | FR/ED | - | - | - |
| 9 | k-ε | | FR/ED | - | - | - |
| 19 | k-ε | | FR/ED | DTRM | - | SIMPLEC |
| 21 | RNG k-ε | | FR/ED | DO | WSGGM | SIMPLE |
| 20 | Realizable k-ε | | ED | DO | - | - |
| 6 | Realizable k-ε | x | FR/ED | DO | WSGGM | PRESTO |
| 7 | k-ε | x | FR/ED | - | - | - |
| 15 | Realizable k-ε | x | FR/ED | DO | WSGGM | PRESTO |
| 2 | Realizable k-ε | | FR/ED | DO | WSGGM | - |
| 5 | k-ε | x | FR/ED | DTRM | - | - |
| 24 | k-ε | | PaSR | DO | - | - |
| 23 | Realizable k-ε | | FR/ED | DO | - | SIMPLE |
| 3 | k-ε | x | - | DO | - | PRESTO |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | k-ε | x | EBU | DTRM | WSGGM | SIMPLE |
| 11 | k-ε | | FR/ED | DO | WSGGM | - |
| 22 | k-ε | | FR/ED | P1 | WSGGM | - |
| 28 | Realizable k-ε | | FR/ED | - | WSGGM | SIMPLE |
| 29 | k-ε | | FR/ED | DO | - | - |
| 30 | RNG k-ε | | FR/ED | P1 | WSGGM | SIMPLE |

(1) Abbreviations: FR, finite rate; ED, eddy dissipation; PaSR, partially stirred reactor; DTRM, discrete transfer radiation method; DO, discrete ordinates; WSGGM, weighted sum of gray gases model; PRESTO, pressure staggering option. Adapted from Rahdar et al, 2019.

The references listed above are identified by the corresponding numbers at the references section.

## 4. CFD-BASED CASE STUDIES

### 4.1 Grate degradation

Excessive temperatures and reducing conditions at the grate surface are well-known conditions that increase the probability of material degradation. It has been assumed that carburization, a process where carbon diffuse into the steel structure, debasing the metallurgical properties of the material, which begins to occur at temperatures of about 975 K, could be a primary cause of grate deterioration in furnaces. In order to avoid such conditions, Duffy and Eaton (2016) employed an unsteady three-dimensional numerical model to predict char combustion near the grate for a variety of scenarios. In this study, the computational domain was divided into three zones, as illustrated in Fig. 2: the windbox, a solid grate and the fuel bed. The authors analyzed the effect of parameters such as the inlet air flowrate, an existing ash layer on the grate, as well as the geometry of the grate itself. In fact, the simulation was restricted around every single grate hole (see Fig. 2). Different hole sizes and spacing between them were considered in the analysis.

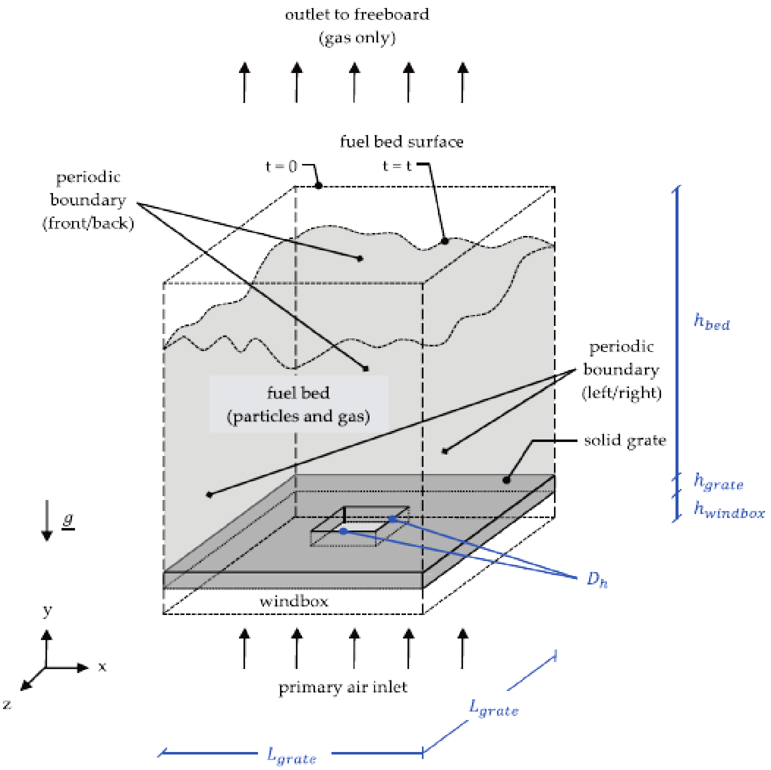


Figure 2. Simulated 3D domain (Duffy and Eaton, 2016).

Predictions indicated that decreasing the size of the holes reduced the peak temperature of the grate for all scenarios examined. Furthermore, this measure is expected to reduce the probability of channeling in the fuel bed and, consequently, improve the furnace performance. The authors remark that the minimum passage size should therefore be limited only by the ash-clogging propensity of the target application. Figure 3 presents the maximum temperature of the grate as a function of peak air speed entering the fuel bed for different hole sizes and airflow rates.

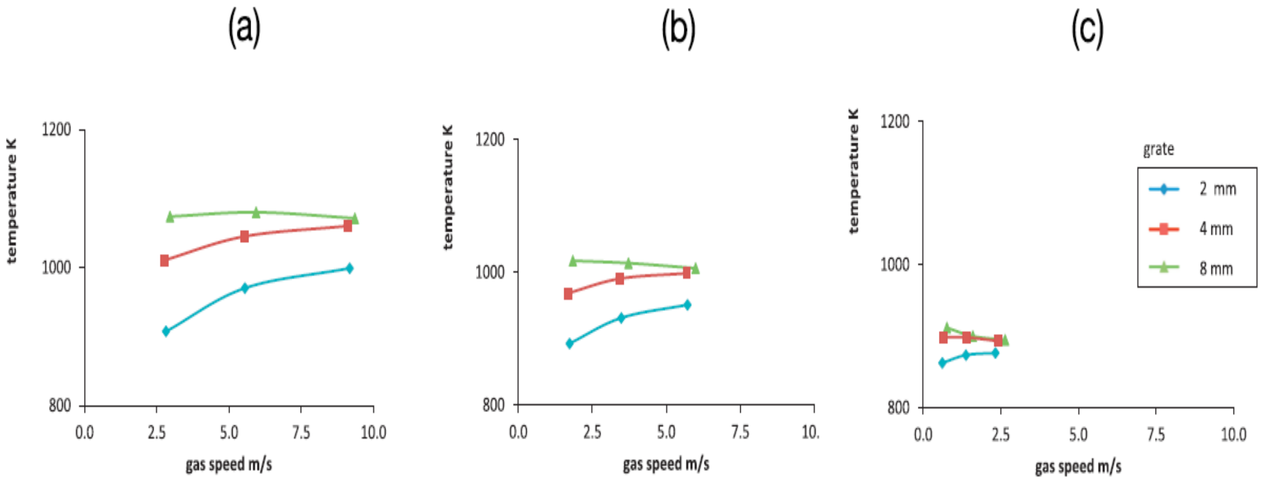


Figure 3. Bare grate - no ash layer: maximum grate temperature as a function of gas speed entering the fuel bed for different hole sizes at an air flowrate of (a) 0.200 kg/m²s; (b) 0.125 kg/m²s; and (c) 0.050 kg/m²s (Duffy and Eaton, 2016).

It can be noted that a lower inlet air flowrate decreased the grate temperatures. However, the overall furnace operation is sensitive to the air inlet, particularly considering $NO_x$ emissions, which limits its use as an optimization parameter.

The spacing between holes also has a significant influence on the temperature of the grate. The larger the spacing between holes, the higher the grate temperatures However, for spacing between holes larger than 30 mm, it implies a lack of oxygen for the combustion process and consequent carburization of the grate material, as shown in Fig. 4.

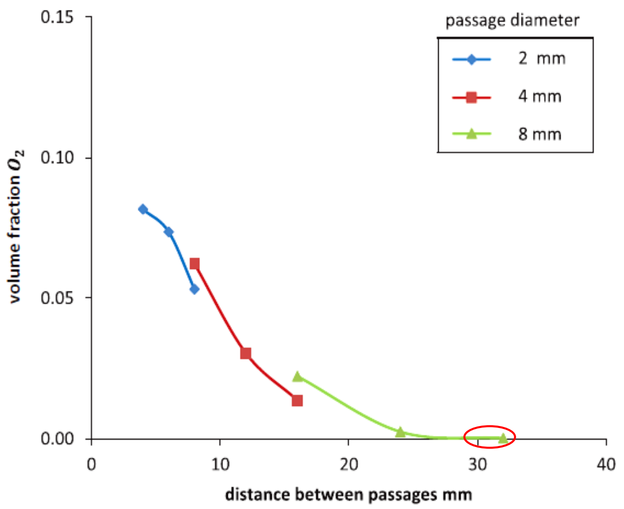


Figure 4. Minimum oxygen content at the surface of the grate for different passage sizes and spacing values at an air flowrate of 0.2 kg/m²/s (Duffy and Eaton, 2016).

Moreover, the authors concluded that the presence of an ash layer on the grate surface promotes a better dispersion of air, favoring chemical reactions near the grate.

### 4.2 Ash deposits formation

The study of ash deposition mechanisms is important in order to minimize thermal resistance, corrosion and problems related to the boiler operation itself. Historically, deposition models were originally proposed for coal and adapted for biomass. These problems are particularly severe in biomass-fired boilers and should, therefore, be considered during the project and operation of such steam generators (Yin et al., 2008). Figure 5 presents typical ash deposits during the combustion of straw and coal.

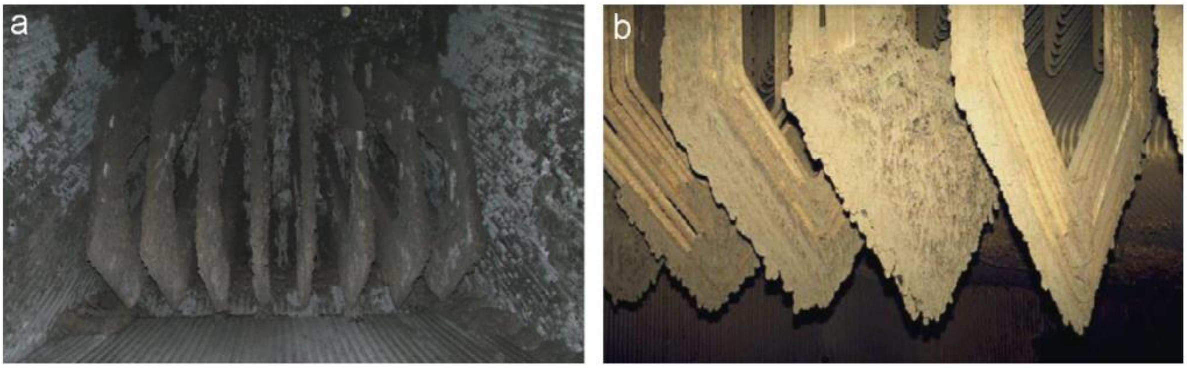


Figure 5. Ash deposits on a boiler's superheater: a) firing straw (Kær et al., 2006 apud Yin et al., 2008); b) co-firing coal and straw (Zbogar et al., 2005 apud Yin et al., 2008).

In the works of Mendes and Bazzo (2012) and Mendes et al. (2017), the growth of deposits in superheater tubes and its effect on heat transfer were studied to determine the decrease in the thermal efficiency of the equipment. The distribution of ash particles and the solution of the flow around a cylinder were obtained through CFD, having good agreement with the characteristics of the real equipment. To assess the growth of deposits, the ballistic and random deposition model was used. With this model, the main growth characteristics can be analyzed without taking into account the various factors that could influence the process. As a result, the models generated a porous structure and its physical and chemical properties were compared with measurements of porosity, pore size distribution and fractal dimension of a typical ash deposit. The existing ceramic phases were quantified using EDX detection and X-ray diffraction of actual samples of ash deposits taken from a power plant in southern Brazil.

In order to assess the influence of ash deposition on the boiler efficiency, a tubular bundle was considered in the analysis, showing a strong effect on the heat transfer from the flue gases to superheating steam. As stated by Mendes et al. (2017), for a 5 mm thick ash deposit with porosity of about 0.3, the flue gases must provide an additional energy of about 30 kW per tube meter to maintain the design conditions.

### 4.3 Air and recycled flue gas staging

In grate-fired boilers, when volatile gases are released from the fuel bed, they mix with the secondary air and combust in the freeboard. This gaseous combustion is generally fast compared to the rate of mixing, presenting high Damköhler numbers. Therefore, fluid mechanics (i.e., mixing) plays a very important role in the pollutant formation, particularly for grate-fired boilers, which have relatively low combustion temperatures (Yin et al., 2008).

Currently, a large number of papers that approach the numerical modelling of grate-fired boilers focuses on the mixing of gases and its optimization. In this context, Rajh et al. (2018) reported results on the CFD modelling of air and recycled flue gas staging in a waste wood-fired grate boiler. The study highlighted the effects of the jet momentum, position and orientation of the combustion air and recycled flue gas streams on mixing, combustion and pollutant emissions from the boiler. For this purpose, six different configurations of secondary and tertiary air nozzles were proposed. The authors concluded that modifying the jets configuration can reduce carbon monoxide emissions up to 86%, from the current 41.0 ppm to 5.7 ppm. Figure 7 shows the CO concentration at the boiler outlet for all scenarios studied.

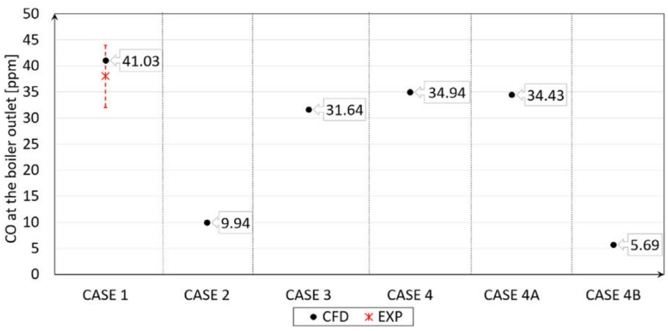


Figure 7. CO concentrations at the boiler outlet (Rajh et al., 2018).

As previously presented, different models have been considered in order to understand the problems related to grate degradation, ash deposits on superheaters and air staging in the combustion chamber. High temperatures have been identified as the main cause of grate degradation, here controlled by changing the grate porosity as well as the primary airflow, and so avoiding peak temperatures above the metallurgical limits. CFD modeling has been widely used for evaluating several phenomena that is hard to measure, such as the velocity and temperature distributions in the furnace and regions close to the superheaters. Finally, all reported works show the need and importance of useful tools in order to improve the boiler design, the thermal efficiency and increase the useful lifetime.

## 5. CONCLUSION

The state of the art and a better understanding of current problems related to biomass-burning boilers were the first objective in this work. In this sense, its application in the development of steam generators was successfully covered, approaching topics such as the investigation of grate degradation, ash deposits formation and primary pollutant emissions. This review contributes for better understanding of the physical phenomena that occur inside reciprocating grate boilers and the results presented here will serve as basis for current and future work at LabCET, in cooperation with Brazilian manufacturers for power plant application.

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## 7. RESPONSIBILITY NOTICE

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