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Biomass early stage combustion in a small size boiler: experimental and numerical analysis

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Abstract

The increment in the world energy consumption and the necessity for a sustainable industrial production, indicate that renewable resources may be key actors for future development. In this scenario, biomass appears fundamental for the smooth transition from fossil fuels to lower carbon footprint technologies, and as a moderator agent within the renewable market. The small size biomass combustion application appears as suitable for smart grid and distributed generation applications, but it is necessary to improve the design tools capabilities and the experimental knowledge of these systems. The present work aims at investigating the thermal behaviour of a 140 kW fixed-bed boiler sited at the Biomass to Energy Research Centre (CRIBE) of the University of Pisa and fed with woodchips. Experimental activities were conducted in order to acquire thermal and chemical data. Moreover, a computational fluid dynamic model was developed and validated. Attention was paid to the fixed bed analysis, and the results showed a good model prediction capability, with respect to the reduced computational demand required.

Keywords: Biomass Combustion; Packed bed simulation; CFD modelling; Biomass emissions

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1. Introduction

The growth of the world energy demand, both by thermal and electrical point of view, introduces new challenges for the environmental impact reduction. For instance, many efforts are made in order to reduce the carbon footprint of the industrial sector and, generally, its pollutant emissions. Biomass may operate as smooth transition agent between fossil and renewable technologies. Moreover, it is particularly suitable for distributed generation and smart grid applications, together with wind and solar plants, in small size combustion systems. However, many technological issues arise that may question about the effective use of these devices. In particular, the large biomass composition variability requires attention about the pollution control [1][2], and needs significant efforts for developing optimization strategies. For instance, the effect of the air distribution on the pollutant emissions from fixed bed systems is widely studied in the literature, especially for laboratory scale or medium size plants. Other authors [3][4] analysed the particulate emissions from biomass stoves for domestic heating, and stated that a good air displacement control strategy could largely reduce the particulate matter emission factors. A bigger 320 kW grate fired boiler was studied by [5], and they also found a strong relation between the CO and NO_x emissions profile and the air displacement and air excess ratio. While relatively many measurements of emissions from biomass combustion can be found in literature, the analysis of the packed bed zone for fixed bed systems lacks experimental data. Indeed, the non-homogeneous motion, heating and volatiles release of the fuel particles control the system performance. Several authors, such as [6], investigated the fixed bed emissions in a laboratory scale system, and they proposed a multi-physical model that is able to predict the thermal and physical behaviour (e.g. the particles shrinking) of the fuel. The understanding of the main mechanisms which involves the biomass evolution inside the combustion system is a key factor into the renewable resources exploitation improvement.
The present work aims at investigating the thermal behaviour of a small underfeed stoker boiler sited at the Biomass to Energy Research Centre (CRIBE) of the University of Pisa and fed with woodchips. According to the research from [7], the main aim is to acquire data from the fixed bed while it operated into nominal conditions. It is important to highlight that most of the literature reports data about biomass combustion into laboratory scale devices or high-power systems, and few data are available on the studied power range. The thermal and chemical data, from the whole early stage biomass combustion volume, were further used in order to validate a computational fluid dynamic (i.e. CFD) model, which was based on the assumption of [8]. Finally, the results were presented, while a comparison between the simulation aided data and experimental values were extensively commented for the case study.

2. Methodology

2.1. Experimental Setup

A 140 kW underfeeded stocker boiler from Standard Kessel Italiana was employed in this research, and the device is sited in the Biomass to Energy Research Center (CRIBE) of the University of Pisa. The system is made of three main parts: the fixed-bed, the combustion chamber and the heat exchanger. The biomass is fed from the bottom by means of a screw conveyor (i.e. 80 mm step and 80 mm external diameter), which supplies approximately 20 kg/h. The air inlet is placed on the upper part of the fixed bed and it consists of 3mm height horizontal channels; moreover, secondary air feed the biomass zone through seven circular ducts with an internal diameter of 20mm. The secondary to primary air flow ratio (i.e. the split ratio λ) could be controlled by means of two sphere valves. No automatic ash removal system is present; ash is hence removed by means of the aerodynamic effect due to the air flow. The exhaust gases passed through a gas to diathermic oil heat exchanger; subsequently the heat is further conducted to a kettle water steam generator. Inside the boiler a thermal probe was housed below the heat exchanger, in order to acquire the flue gas temperature. The probe is shielded on purpose to avoid radiative effects. A suction probe was also placed above the fixed bed, with the capability of rotating and translating along its own axis; such probe was capable to collect gases from the surface of the fixed bed in early stage conditions. Particularly, 6 positions where selected as suitable for the species concentration analysis and corresponding to the secondary duct sites. While the translational action covered the longitudinal bed length, 10° rotation allowed the probe to collect gases from the side and from the middle line of the fuel bed surface. The gases were sampled and analyzed continuously (i.e. each 3 seconds) by means of a Fourier Transform Infra Red analyzer (FTIR) with an integrated suction system that collected gas directly through the gas probe. Each measure was performed for 5 minutes at least, this allowed to provide an average and standard deviation error to the species measurement. Moreover, 12 K-type thermocouples were displaced inside the reaction zones into different positions in order to acquire the temperature profile of the burning biomass. Particularly, 4 main sample positions were detected below, on and above the fuel surface (i.e. Low L, Middle M, Upper U and Side S measurement tag), respectively. Hence, three sensors per position were employed (i.e. Left L, Centre C and Right R). A sketch of the system is provided in Fig. 1(a). Furthermore, the positions of the thermocouples are shown in Fig. 1(b). It is important to notice that the side left sensor position (T_{SL}) resulted in poor quality of the measures and was not considered into the results. The fixed bed thermocouples, together with the oil, the flue gases, the air temperature (i.e. T_o, T_f and T_a respectively, where in is the inlet and out the outlet tag) and the mass flow sensors signals (i.e. m_{ap} for the primary and m_{as} for the secondary

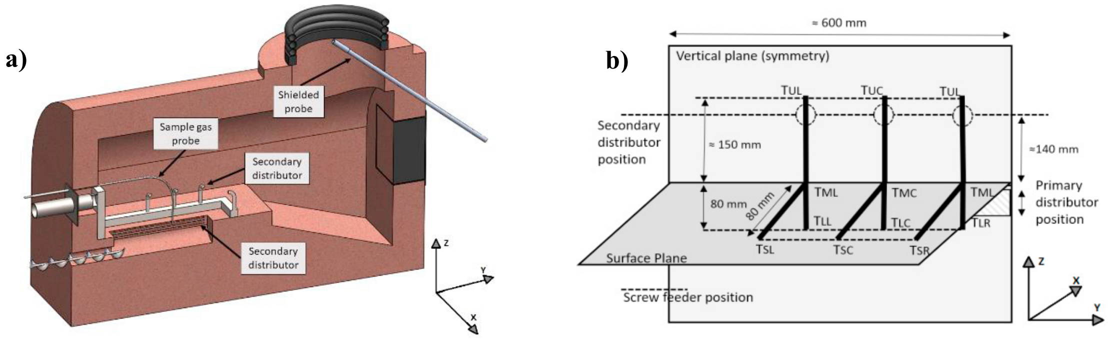


Fig. 1. (a) boiler system overview; (b) thermocouples position scheme

air mass flow) were acquired by means of a National Instrument device. The boiler control system was provided with a secondary to primary air feeding mass flow split valves, and through these it was possible to control the air distribution inside the bed. An Environnement SA test bench was used in order to acquire the O_2, CO_2 and CO concentrations of the exhaust gases. The control system scheme and the acquisition lines are represented in Fig. 2 [7]. The employed fuel was a Poplar woodchip biomass from short rotation forestry dedicated area of the CRIBE.

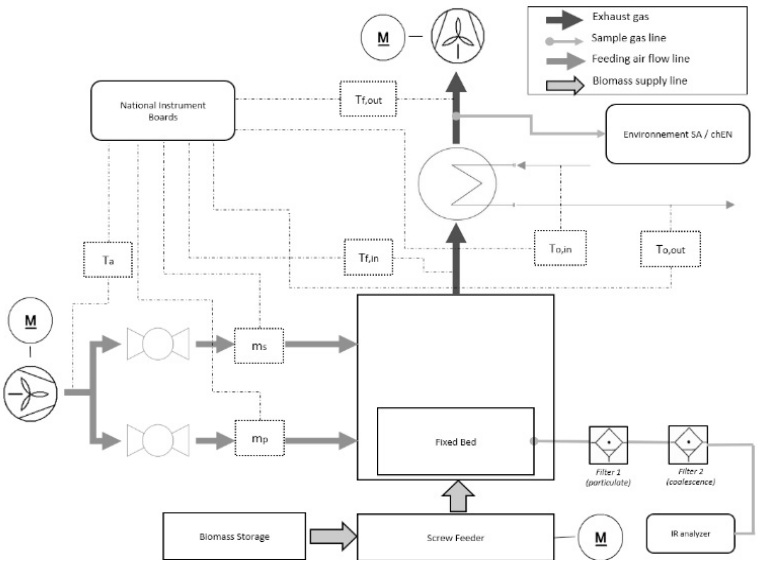


Fig. 2. Control scheme and acquisition lines of the boiler

The fuel was harvested in April 2017, dried and properly stocked into a cool and dry place. Before the use in February 2018, the fuel was characterized by means of proximate and ultimate analysis, as shown by Table 1.

Table 1. Proximate and Ultimate analysis of the fuel

$C[\%_{db}]$	$H[\%_{db}]$	$N[\%_{db}]$	$VM[\%_{db}]$	$FC[\%_{db}]$	$Ash[\%_{db}]$	$Moisture[\%_{ar}]$	LHV[MJ/kg]
49.01	5.83	0.57	82.46	15.35	2.19	9.28	18.38

Moreover, the dimensional analysis of the biomass was performed according to the EN 15149, and the mean diameter d_{50} = 11.46 mm and the maximum diameter d_{max} = 87mm.

2.2. Numerical Model

A CFD model of the whole fixed bed and combustion chamber was developed with ANSYS Fluent v16.0, in order to test the model capabilities of representing the fluid dynamic and chemical behavior of the biomass products. The biomass bed was represented by means of a porous media with sources/sinks of chemical species and temperatures [6]. The characteristics of the biomass bed were chosen according to the features of the fuel involved into the experimental analysis. Particularly, a porosity γ = 0.73 was measured as one minus the ratio between the packed and the standard fuel density (i.e. 450 kg/m^3). The momentum losses were calculated according to the Ergun equations for packed bed porous media [7], which parameters α (i.e. the porous bed permeability) and C_2 (i.e. the inertial porous coefficient) are reported in Equations 1 and 2.

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

$$C_2 = \frac{3.5}{D_p} \frac{(1-\gamma)}{\gamma^3} \tag{2}$$

In order to reproduce the reactions inside the fuel layers, a volumetric source S_i was created for the CO, CO_2, water vapor, O_2 and volatile species, as well as for energy through a user defined function. Logically, the source for O_2 is negative as it is consumed for char oxidation. The species and heat generations were calculated referring to the complete combustion reaction scheme. Furthermore, the values were distributed on the fixed bed volume (i.e 0.0047 m^3) non-homogeneously to take into account that the screw conveyor was unable to push the biomass up to the opposite edge with respect to the feeding. In fact, from the fuel inlet to the 85% of the fuel bed length l (i.e. 0.6 m), constant sources S_{il} were implemented, while after the full volume length the sources linearly diminish to zero. Hence the total calculated source values are distributed within the corrected pattern, according to Equation 3.

$$lS_i = \int_0^{0.85l} S_{i,l} dy + \int_{0.85l}^{l} S_{i,l} \frac{0.85l - y}{0.15l} dy \tag{3}$$

This correction was related to the experimental observation that in the end of the fixed bed (i.e. opposite position from the screw feeder) the fuel, which is mainly converted and dimensionally reduced, was removed for aerodynamic effect of the primary and secondary air mass flows. Moreover, the water release was concentrated into the first 15% of the length, according to the drying phase which occurs in the first region of the fixed bed. The modifications were implemented by means a C++ routine through an User Define Function (UDF), and Table 2 reports the source S_{il} value for each i-th term.

Table 2: Source values for the UDF terms

Source term Tag	Source term S_{il}	Unit
Energy	90661	[W m^{-3}]
Volatiles	0.469	[kg s^{-1} m^{-3}]
O_2	0.233	[kg s^{-1} m^{-3}]
CO_2	0.318	[kg s^{-1} m^{-3}]
H_2O	0.411*	[kg s^{-1} m^{-3}]
CO	0	[kg s^{-1} m^{-3}]

*value distributed into the first 15% of the bed volume

Similar correction was applied to the porosity pattern, which linearly reached $\gamma = 1$ at the end of the fixed bed. The CFD code solved a set of stationary Reynold Averaged Navier-Stokes equations for continuity, momentum, energy conservation and species transport for the single-phase reactive turbulent flow. Reynolds stresses were closed by means of the standard k-ε model. Reaction rates were assumed to be controlled by turbulent mixing by applying the Eddy Dissipation Model (EDM). Volatiles were treated as a pseudo component, and by a two-step reaction model. It is important to notice that the CO production was totally managed by the solver, and according to the literature a CO_2/CO ratio was taken as 0.8. The same approach was employed in another published paper [8] and, in any case, these assumption are quite common in the literature [10] especially when the reduction of computational time is determinant. By the other hand, more complex and reliable models, such as the Eddy Dissipation Concept (EDC), are used by other authors [11], [12]. In order to take into account the radiative contribution, the P1 model was implemented together with a Weighted Sum of Gray Gases for the radiative properties estimation [13]. The domain consisted in 800k hexahedral grid, while the fixed bed was modeled with 10k hexahedral cells. The main boiler model boundary conditions were reported in Figure 3. It is important to notice that, because of the symmetry of the boiler, the domain represented half of boiler, with Z-Y surface as mirror plane.

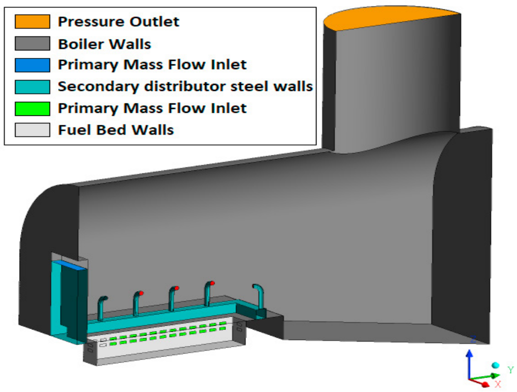


Fig. 3. Boiler boundary conditions overview

2.3. Experimental boundary conditions

In order to perform both experimental tests and simulations into reliable conditions, a target air excess ε between 1.5 and 2.5 was chosen, together with a secondary to primary air feeding flow λ between 0 and 1. Within these values, the operation of the boiler remained stable and all the sensors worked in the proper range. Table 3 reports the employed boundary conditions for the tests, both target and experimental result conditions.

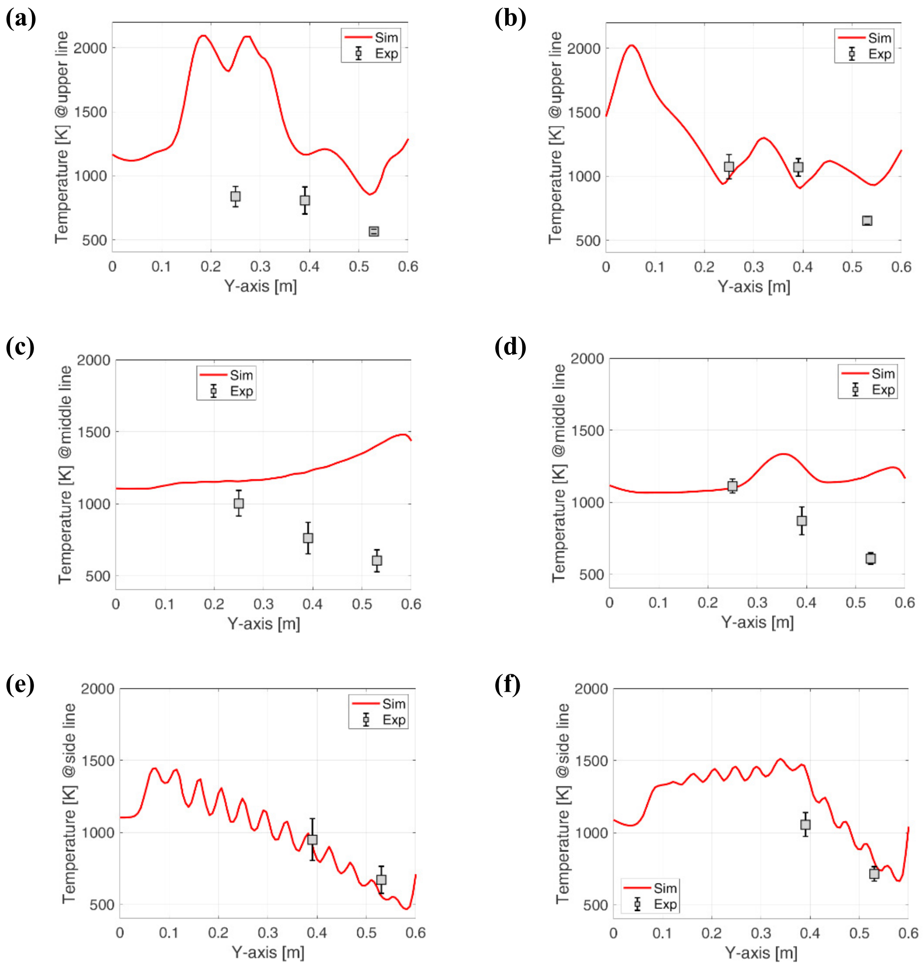
Table 3: Test boundary conditions, both target (Target) and Experimental measured (Exp) ones.

	ε [–]		λ [–]		M_{ap} [kg/s]	M_{as} [kg/s]
	Target	Exp	Target	Exp	Exp	Exp
ID1	2.5	2.09	0.7	0.75	0.054	0.011
ID2	1.5	1.38	0.2	0.19	0.031	0.021

It is important to notice that the simulations employed boundary conditions were the same of the experimental ones. Each test conditions were maintained for around 40 minutes, and an average temperature was calculated along the time, together with a standard deviation error.

3. Results and Discussion

The performed simulations required around 8 hours each to satisfy the convergence criteria, with 8 processors at 2.2GHz frequency calculator. The collected experimental data and the simulated values were compared and represented along the Y-axis for the different fixed bed positions investigated. Moreover, both the ID 1 and ID 2 were compared, in order to highlight the capability of the model to predict the correct patterns in different conditions. Firstly, the temperatures behavior was reported in Figure 4.



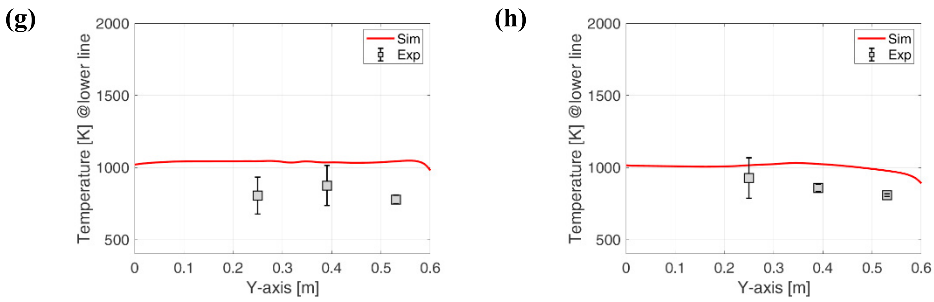


Fig. 4. Experimental (Exp) and predicted (Sim) temperatures in the fixed bed for ID1 (a,c,e,g) and ID2 (b,d,f,h)

The temperature predictions and the experimental data have a good accordance for what concerns the lower and the side lines (Figure 4(e,f,g,h)) and, in most of the cases, they are within the experimental measurement error. When higher sample lines are considered, the data accordance decreases. The simulated data show a non-uniform temperature behavior (Figure 4(a,b)), that usually occurs into high turbulence flow conditions. It is possible that when the secondary air flow increases (i.e. λ increases), the prediction accuracy of the gas motion field results reduced, and so the reactions that occurs above the fixed bed. Therefore, when an higher weight is given to the gas phase turbulent combustion above the bed, the accuracy of the model appears significantly lower, as shown by Figure 4(a,c) and Figure 4(b,d), respectively. It is also interesting to notice that the points at Y = 0.54 m results experimentally in lower temperature with respect to the others. This fact is due to the high biomass consumption rate that does not allow the fuel to reach the end of the fixed bed properly. In fact, the bed-end area usually acts as partially exhaust fuel, char and ash deposit, which significantly affect the bed height and products composition. Despite a proper UDF was implemented in order to take into account these effects, the ash and char deposits can be only taken into account with significantly higher computational efforts. For the produced species analysis, Figure 5 reports the CO behavior on the fuel plane sample points.

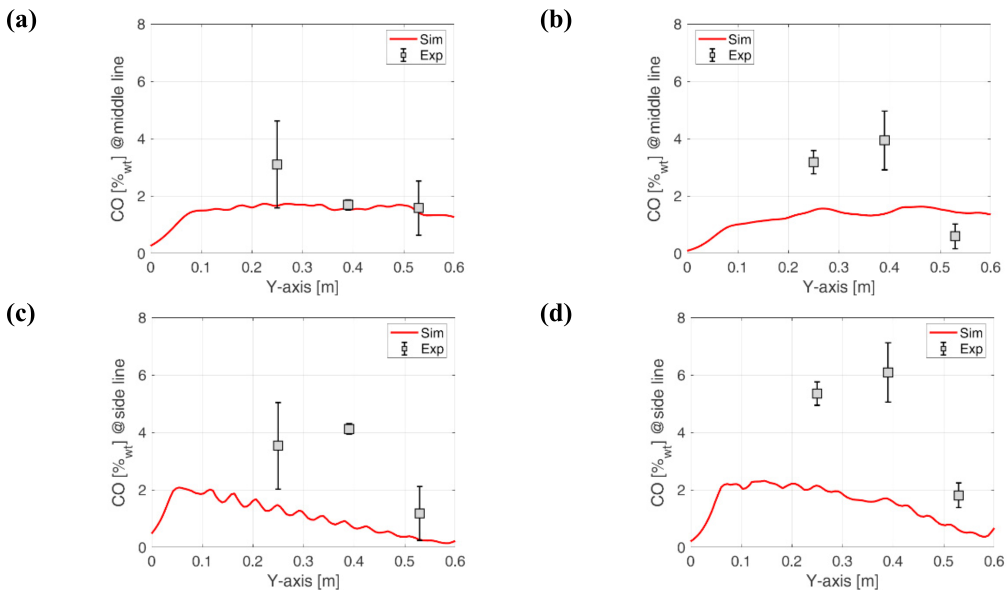


Fig. 5. Experimental (Exp) and Simulated (Sim) CO specie behavior into the fixed bed surface for ID1 (a,c) and ID2 (b,d)

Despite for the middle line the data present a good agreement within the error range, the experimental side values results significantly higher values than the simulated one (i.e. around 2 times). Because the CO presence is usually an indicator of poor oxygen availability, it shows that the O_2 is non-uniformly distributed on the fixed bed surface along the X direction. This effect is related to two main factors: firstly, the oxygen percentage decrease from the primary air source to the middle bed line, because of its consumption. Secondly, the impact of the primary flow force varies the bed porosity, which results in higher compactness on the middle region. The combination of these two phenomena affect the fixed bed surface emissions, and it can be corrected by using a proper spatial correction for both the porosity and species production through an improved UDF. It is also important to notice that the lower amount of CO fraction in gas (i.e. from the side zone) is related to lower amount of energy released into the gas phase. This fact is also supported by lower temperature found in middle and upper lines with respect to the experimental ones. Therefore, the use of an improved volatile gas speciation which also takes into account CH_4 and H_2 (i.e. instead of a pseudo-component) would largely improve the reliability of the CFD results.

4. Conclusions

Biomass combustion appears interesting for smart grid and distributed generation applications. In order to improve the design capabilities, new experimental data are appealing to drive the development of new modelling strategies. In this work, a 140kW biomass boiler placed in the CRIBE facility of the University of Pisa was employed in order to acquire early stage combustion data from the fuel fixed bed. Moreover, a numerical model was developed with ANSYS Fluent software in order to reproduce the fuel bed thermal behavior and the main species production. The comparison between the simulated and experimental data showed a good values agreement for the temperatures and the chemical species in the biomass bed volume. By the other hand, several efforts must be taken into consideration in order to improve the model reliability, especially when the secondary combustion stage has a significant weight on the combustion behavior. For instance, the introduction of more detailed chemical models for gaseous reactions can increase the prediction efficiency for the main boiler emission species, such as CO, CO_2 and nitrogen oxides. Finally, the implemented porous model resulted in affordable results in terms of temperature and carbon monoxide values with respect to the measured data.

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