Numerical Tools Developed to Predict the Combustion Behavior inside a 20 kW Pellet Boiler

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Abstract.
The combustion of pellets is an essential source for room heating appliances and sustainable and renewable energy deployment. This is the main motivation that makes combustion technologies subject, in recent years, to constant developments and investigation. However, the formation of pollutant emissions accompanies the thermal conversion of pellets and, some environmental considerations and restrictions are becoming more restrictive, requiring preventing emissions to the atmosphere. To achieve these demands, stable and efficient combustion is imperative. Consequently, to improve biomass combustion in automated small-scale pellet boilers, this works presents a numerical model to predict the combustion behavior inside the equipment and the implementation of a Design of Experiments based on the Taguchi method to perform an experimental campaign and understand the influence of several parameters. The CFD results were able to predict the arrangement of the particles on the grate, the temperature profile of the particles, and the main gas species concentration inside of the boiler with acceptable accuracy compared with the experimental measurements. In combination with the experimental work, recommendations to reduce pollutant emissions and obtain stable combustion were indicated.

Keywords: Biomass; CFD; Combustion; Numerical Model; Pellets.

1 Introduction

Biomass combustion is one of the most thoroughly investigated topics nowadays, and it is a promising research area. The main reason is its complexity in terms of conversion since it involves simultaneous multiphase fluid flow, chemical reactions, heat (convection and radiation), and mass transfer. Within the scope of combustion in small-scale reactors, concerning pellet boilers, represents an evolution of traditional residential biomass systems considered inefficient and pollutants [1]. However, there are some concerns regarding the operation of these types of boilers requiring continuous progress in its technology to achieve optimal combustion with low emissions and prevent problems during continuous operation.

Hence, in the last decade, some authors conducted experiments to assess the design strategy [2–6], operational problems related to ash behavior in small-scale pellet boilers [7–9], and emissions (particles [10–16] and gaseous emissions [17–23]). These works are relevant to understanding the equipment performance and efficiency and understanding which are the most appropriate operating parameters to obtain low emissions. However, to reduce the costs and the time needed to carry out the experiments, different numerical tools for combustion behavior analysis are becoming popular with the advances of computational resources and technologies.

Computational Fluid Dynamics (CFD) tools have been increasingly used in optimizing the combustion process, and they have become essential in boiler design and operation troubleshooting. Furthermore, CFD modeling can also be helpful to analyze different working conditions and estimate a multitude of variables inside the whole domain, particularly pollutant emissions [24,25]. However, modeling biomass combustion is more complex than gaseous fuels, and most CFD codes are limited in handling biomass conversion. In this sense, from the implementation point of view, there are two main approaches commonly followed in CFD simulation of fixed-bed biomass boilers to account for the conversion of the solid particles in the bed [24,25]. The first approach is to develop a model that predicts the evolution of the thermal conversion of the bed and, in doing so, the inlet conditions for the gas phase modeling in CFD simulations will be computed [26–30]. With this approach, the combustion process in the bed and the gas phase are treated separately. However, this empirical nature does not fully capture essential aspects, and the influence of physical phenomena occurring in the boiler, particularly in the bed, cannot be considered.

In contrast, the second approach fully integrates the bed region in the CFD simulations [31–35]. This method avoids the separation of the bed and the gas phase, allowing for the treatment of the interactions between the gas and solid phases on the surface of individual particles, and the movement of the bed particles is treated in the same software [31–33] or separately using a discrete element method [34,35]. In general, this is the most complex approach. The solid phase is integrated into the mathematical model, which essentially characterizes the thermal conversion of the solid particles and the interactions between the solid and gas phase within the fuel bed.

Nevertheless, the accuracy of these models is committed by their assumptions and the physical models' capability to predict the phenomena. It is in this sense that another approach appears. Recent developments related to machine learning algorithms and big data provide platforms to develop advanced process data analytics to predict, for instance, boiler performance and emissions. In this way, artificial neural networks are becoming used as an alternative tool to simulate complex problems. The application of this approach to small-scale boilers is still limited. Böhler et al. [36,37] applied an emission limiting model-based predictive controller to minimize the carbon monoxide emissions, and is one example of the pertinence of this model. However, the application to the large-scale boiler is more frequent to obtain operational insights and guidelines [38], to predict flue gas temperatures [39,40], to develop a system for predictive maintenance [41], to optimize the thermal efficiency and performance [42,43], and also to predict the NOx emissions [44,45].

In this context, the present study aimed to develop a numerical model able to simulate the combustion process in a 20 kW pellet boiler. This study was developed using the ANSYS Fluent software, which is often used to analyze the combustion processes. However, as previously mentioned, modeling the combustion of the solid particles is not allowed, and only the combustion of the flue gases after the combustion above the bed zone is possible. Consequently, ANSYS Fluent was combined with a fully integrated packed-bed model. An experimental test was also performed to validate the results and to study the influence of the grate dimensions, excess air, the thermal load, and the split ratio of primary and secondary air on the fuel bed temperature, gas emission, boiler efficiency, and agglomeration on the grate.

2 Materials and Methods

2.1 Small-scale Reactor and Fuel Properties

Fig. 1 presents a schematic diagram of the test facility used in this study. This facility consists of one boiler, a fuel storage compartment, an external cooling system, a gas analyzer unit connected to the data acquisition system. The boiler works under forced draught, and its operation was programmed with LabVIEW National Instruments. This program automatically regulates the air flow rate by adjusting the draft fan speed and the fuel feeding rate by changing the screw feeder movement. The flue gases are forced to exit the boiler through the use of a draft fan and, consequently, fresh air enters the combustion chamber, due to the induced pressure gradient, by the primary and secondary air channels. In this way, the boiler includes independent primary and secondary air inlets uniformly distributed along the grate and at the burner walls, 70 mm above the grate, respectively. Furthermore, the primary to secondary air ratio is adjusted due to the different primary and secondary air tube diameters.

To start the combustion, the fuel is supplied by gravity from a storage tank, which has a digital scale underneath (accuracy of 0.05 kg) to measure the fuel consumption through an external conveyer to the boiler by a helical screw. Then, the ignition is accomplished with the aid of an electrical resistance placed on the grate.

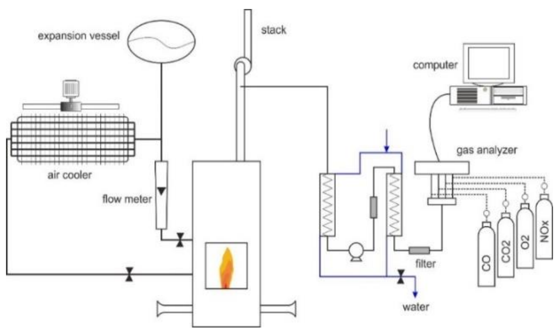


Fig. 1. The layout of the test facility.

Even before the flue gases are released into the exhaust, a gas sample is extracted from the final section of the stack using the gas analyzer apparatus. This equipment includes a sample gas pipe system from the stack, vacuum pump, cooling system, filters, and calibration gases. Multi-Gas Analyzer, model SIGNAL9000MGA, measures the gas emissions including O_2, CO_2, and CO. Before the experiments, the gas analyzers are calibrated in a nitrogen diluent with concentrations for CO=5000 ppm, O_2=20%, and CO_2=10%. Then, the vacuum pump is used to extract the sample and take it to the gas analyzer. Before entering the vacuum pump, the sample is cooled and filtered to remove moisture and particles.

In addition to all equipment used to characterize the combustion behavior inside the grate there are 4 thermocouples (K-type) installed to measure the temperature inside the fuel bed. To determine the boiler efficiency, also 2 thermocouples (K-type) are installed at the inlet and outlet of the heat exchanger to measure the hot and cold water temperature. Table 1 presents the baseline operating conditions of the pellet boiler. The boiler operates at 20 kW of thermal power with 50% excess air, and the split ratio of primary to secondary air was 37/63%.

Regarding the fuel, commercial pine wood pellets, with 6 mm diameter, certified according to the European Standard 14961-2 and ENPlus® A1, were used during the experiments. Their composition is summarized in Table 2. The ultimate and proximate analysis values and the calorific value of the pine wood samples correspond to the samples obtained after the milling process. The technical specifications of European standards were followed to perform the analyses, and a Leco TruSpec Series measured the sulfur content of the samples. To measure the heating value, a calorimeter, Leco AC500 was used. The pine wood lower heating value estimated was 17.10 MJ/kg.

Table 1. Operating conditions.

Parameter	Values
Fuel flow rate (kg/h)	4.3
Primary air mass flow rate (m^3/h)	30.4
Secondary air mass flow rate (m^3/h)	59.6

Table 2. Elemental analysis of pine wood pellets.

Proximate Analysis (wt.%, as received)		**Ultimate Analysis** (wt.%, dry ash free)	
Moisture	6.90	Carbon	50.90
Volatile matter	77.80	Hydrogen	5.30
Ash	0.60	Nitrogen	1.55
Fixed carbon	14.70	Sulphur	0.03
		Oxygen	42.22

2.2 Experimental Conditions and Data Analysis

A set of experimental tests was planned according to the Taguchi method to analyze the influence of the most important parameters on the combustion performance, including excess air, power, primary to secondary air ratio, and grate area. These parameters were considered to be the most dominant in the combustion of the pellets. In this plan, three different levels for each parameter were selected, as presented in Table 3. If Taguchi's method was not applied in this study, the number of experiments would reach a total of 81 (34). However, with the selection of an appropriate orthogonal array, this number is highly reduced to 27.

From the experiments, several parameters are recorded, including the gas emissions (CO, NO_x, O_2, and CO_2) and the temperature of the fuel bed measured at four different positions (5, 15, 25, and 60 mm from the bottom) in the center of the fuel bed. Furthermore, the CO emission is the parameter that better describes the combustion quality during the combustion process. Meanwhile, during long operation periods, as the CO value could fluctuate and increase significantly with the fuel bed rise, the CO emission is considered in this study as the factor for the occurrence of those instabilities in the fuel bed.

Regarding the procedure of the experiments, the operating conditions are previously determined for each run and configurated in the LabVIEW program. Then, the pellets are introduced automatically in the combustion chamber, and the ignition starts after around 95 seconds. After that, the combustion process tends to stabilize after about 8 minutes, and the experiments are carried out for more approximately 1 to 4 hours. From this period, the average values of gas emissions and temperatures are calculated.

Table 3. The different values considered for the experimental plan.

Parameter	Values		
Excess Air (%)	50	70	110
Power (kW)	10	13	16
Air Split Ratio (-)	20/80	30/70	37/63
Grate Are (mm^2)	90 x 75	115 x 75	115 x 96

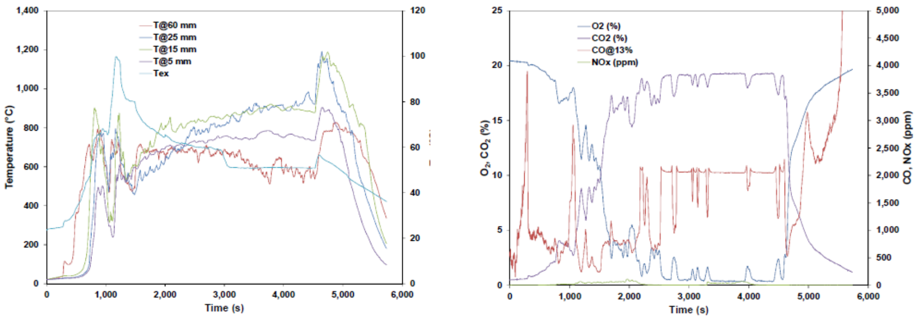
2.3 Modeling of CO emissions and Combustion Behavior

CFD simulations in combination with detailed sub-models for the solid fuel conversion have been developed regarding numerical studies. This methodology allows clear visualization of the bed arrangement and the solid particles' conversion on the grate. Consequently, the treatment of the interactions between the gas and solid phases on the surface of individual particles and the movement of the bed particles are allowed. These simulations are very useful to predict information about the pellets conversion, which is very difficult with the available experimental instruments. Consequently, to predict the arrangement and temperature profile of the particles and the main gas species concentration inside the boiler. The simulation and procedure developed in the numerical study are described in detail in [46].

3 Results and Discussion

3.1 Experiments

Figs. 2 and 3 present an example of the temperature and gas emissions values recorded during one of the experiments where poor combustion with high CO emission and a stable combustion process occurred, respectively. The experiments were performed with the same grate area, a power of 10 kW, and the difference was the air split ratio and excess air. For the first case, the air split ratio and excess air were 37/63 and 50% and for the second case was 30/70 and 110%, respectively. This difference in the air supply, where mainly more secondary air exists than air supplied below the grate, results in a reduction of around 4.5 and 1.8 times in the average CO and NO_x emissions, respectively. With this reduction, more oxygen is available inside the combustion chamber, one of the most critical factors in completely oxidizing the carbon monoxide emissions.



a) b)

Fig. 2. Temperature and emissions profiles for one of the experiments with poor combustion.

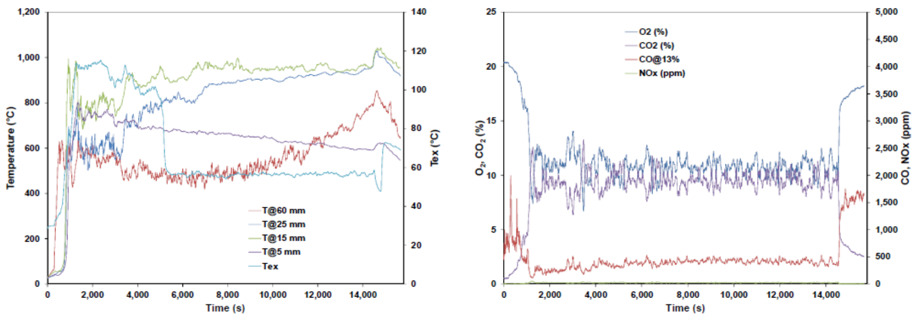


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Fig. 3. Temperature and emissions profiles for one of the experiments carried out.

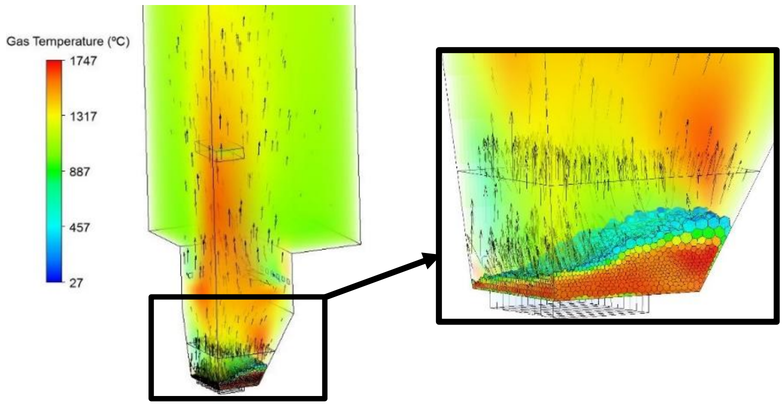
In addition to this example regarding the flue gas emissions and temperatures, it was observed that instabilities could occur over long runs during the experiments. These were identified with a sudden rise in the fuel bed height that would lead to an increase in emissions and, ultimately, to a collapse of the combustion, which may be a consequence of the lower combustion rate (accumulation of unburned pellets on the grate). This is a reason why boiler manufacturers introduced a control strategy that periodically cleans the fuel bed. As an example of the occurrence of this problem, Fig. 2 b), after 1 hour of the experiment, presents an increase in the CO emissions that were observed due to the fuel rising in the grate.

Furthermore, as an overview of the Taguchi method, it was observed that the air split ratio contributes 21.45% to CO reduction, followed by power with 14.59%. The medium power (13 kW) results were the ones with the highest efficiency or lowest CO emissions. The excess air, grate area, and split ratio have the same tendency on the efficiency and CO emissions, where higher thermal efficiency at lower and middle values of those parameters was achieved. The average temperature values in the fuel bed indicated that the highest temperature was observed at 15 mm, followed by 25, 5, and 60 mm in height. The most important parameter contributing to the fuel temperature is the air split ratio and power.

3.2 Numerical model

The numerical study was performed considering the operating conditions presented in Table 1. Figs. 4 and 5 show an example of the results obtained with the numerical model developed. As can be observed by the carbon monoxide emissions, the CFD results showed that the operation of the boiler allows an effective mixing between the combustion air and the flue gases inside the combustion chamber. The mixing between the flue gases and the air inside the boiler is always significant to improve the combustion efficiency and reduce pollutant emissions. As shown in Fig. 4, due to the penetration of the secondary air nozzles, there is a sudden increase in the temperature due to the mixture of the flue gases with the air supplied by the nozzles. Therefore, the configuration of the air jets is vital to improve the combustion process. However, the release of the flue gases is more evident in the region near the middle of the grate because, in this place, there are fewer particles and, therefore, the flow resistance is lower.

The CFD results, compared with the experimental data, present a generally good agreement since they are close and within the maximum and minimum values. However, the CO concentration predicted is lower than the experimental observation, probably due to the simplicity of the global combustion reaction scheme employed in CFD simulation. More details about the CFD model and results can be found in [46].



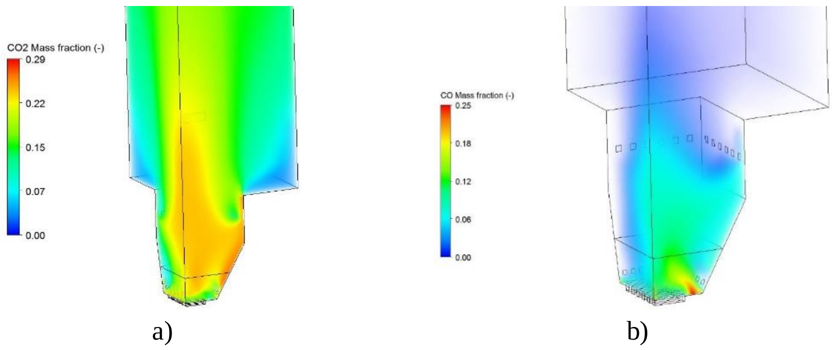


Fig. 5. Profiles of the mass fraction of the main gas-phase components: (a) CO_2, (b) CO, and (c) O_2.

Fig. 4. The temperature profile of the flue gases inside the boiler.

4 Final Remarks

This paper presented an analysis of the combustion behavior of a 20 kW prototype pellet boiler through an experimental campaign and a computational model. The main results and key findings led to the conclusion that:

- The combination of the experimental and numerical work allowed a deeper understanding of pellets combustion and provided a tool for improving the efficient use of biomass and decrease pollutant emissions.
- The set of experiments were very useful to better understand the different operating conditions of a commercial pellet boiler and obtain information to validate the numerical model developed to evaluate the combustion performance of the equipment.

- During the experiments, it was observed that instabilities could occur over long runs. These were identified with a sudden rise in the fuel bed height that would lead to an increase in emissions and, ultimately, to a collapse of the combustion.
- From the Taguchi plan of experiments, it was possible to understand with a reduced number of experiments the influence of the four parameters identified with the most impact in the combustion performance.
- From the numerical modeling perspective, the main assumptions, geometric model and its discretization, methodology, and physical models employed seem correct.
- The prediction of the main variables of the solid and gas phase and the temperature of the flue gases above the grate where the pellets conversion takes place has been made with a reasonable level of accuracy.

The combination of the experimental research and the development of the numerical model is expected to reduce pollutant emissions and costs, leading to the improvement of the process used in commercial pellet boilers. Also, as future work, the data obtained during the experiments will be applied to machine learning algorithms to analyze the conditions inside the prototype pellet boiler and anticipate the appearance of specific phenomenon that results in maintenance actions or high emissions.

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