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CFD modelling of biomass boilers - a review of the state of the art

Modelado CFD de la combustión en calderas de biomasa – Revisión del estado del arte

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ABSTRACT

Keywords:
Combustion, Solid biomass, Modelling, Computational fluid dynamics.

Combustion is the main method of converting biomass to energy, either by direct heating systems or by boilers. By means of CFD models, it is possible to optimize the behavior of those systems and improve significantly its performance, without incurring the economic and environmental cost of experimental studies. However, modelling of biomass combustion is a complex process that requires a large number of sub-models and computational resources for a detailed description, therefore, different approaches have been developed which depend on the system and simulation objective. In this work, a review of the state of art of modelling of solid biomass combustion in the last years is presented, including classification, description and analysis of several of the main models about the subject.

RESUMEN

Palabras clave:
Combustión, Biomasa sólida, modelado, dinámica de fluidos computacional.

La combustión es el principal método de transformación de biomasa en energía, ya sea en sistemas de calefacción directa o en calderas. Por medio de los modelos CFD se puede optimizar el funcionamiento de estos sistemas y lograr mejoras significativas en su desempeño, sin incurrir en los costos económicos y ambientales que los estudios experimentales acarrean. No obstante, el modelado de la combustión de biomasa sólida es un proceso complejo que requiere de gran cantidad de sub-modelos y recursos computacionales para una descripción detallada, por lo que se han desarrollado diversos enfoques que dependen del sistema a modelar y del objetivo de la simulación. En el presente trabajo se realiza una revisión del estado del arte sobre el modelado de la combustión de biomasa sólida en los últimos años, incluyendo la clasificación, descripción y análisis de varios de los principales modelos desarrollados sobre el tema.

Introduction

According to ISO 16559:2014, biomass can be defined as any material of biological origin, except those that have undergone mineralization processes such as those originating from oil, coal and natural gas [1]. It has several advantages when used as an energy source, such as: neutral CO2 emissions, energy independence in areas of difficult access and the possibility of using waste material [2].

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Therefore, several methods have been developed for its conversion into energy, of which combustion is the most widely used, either for direct heating or for use in boilers [3], [4]. This is a complex process composed of two physical stages of matter transfer and a chemical reaction stage [2], the first two stages correspond to: diffusion of the comburent through the gas phase and ashes to the unreacted zone, and diffusion in the opposite direction of the reaction gases; while the chemical reaction stage of combustion is divided into three phases: drying, pyrolysis and combustion of the carbonaceous residue. In drying, all the water in the fuel evaporates, it is an endothermic process that occurs when the fuel reaches 100 °C; in pyrolysis, the fuel decomposes into volatile gases, tar and carbonaceous components, in this stage the gases combust producing flame while the O_2 pressure remains very low near the carbonaceous surface so that the latter does not combust; Finally, the combustion of the carbonaceous residue (char) occurs when the volatiles are oxidized and approximately 20% of the initial mass remains with approximately 90% porosity, the char contains high amounts of carbon so its calorific value is high, this is a much slower stage than the previous ones so it is the limiting of the overall chemical reaction. It is worth mentioning that during combustion not a single reaction occurs but a series of chain reactions, for example in the combustion of methane (CH_4), the simplest of hydrocarbons, up to 40 elementary reactions are involved [5] that take place during the mentioned stages.

Current combustion furnaces usually present problems of low efficiency, heat load instability and slag [6], [7], which represents a need for research to improve the performance of this equipment and in turn the reduction of pollutants, since the increase in efficiency leads to a significant decrease in emissions and fuel consumption; analyses have shown that a 1% increase in the efficiency of biomass-fired power plants leads to a 3% reduction in their CO_2 emissions [4]. A valuable tool to improve the performance of biomass combustion systems is CFD (Computational Fluid Dynamics) simulation, which can be used to improve the design and operating conditions of such systems without incurring the economic and environmental costs of experimental studies [8], [9]. However, the advantages of numerical methods in the optimization of biomass combustion are not fully exploited, because simulating it requires several sub-models for thermochemical conversion and sufficient computational resources [10] - [14]. A detailed description of the sub-models used in modeling solid biomass combustion is presented in the works of Dernbecher et al. [10], Karim and Naser [12], Bhuiyan et al. [4] and Khodaei et al. [15]. The aforementioned requirements make the modeling of solid biomass combustion a complicated process, to the point that the conversion, transport and reaction processes that take place there are not currently contemplated in commercial simulation tools [11], [13]. That is why several types of models and modeling approaches have been developed to satisfy different simulation requirements in different combustion systems. In the present work, a complete review of the state of the art on CFD modeling of solid biomass combustion is carried out, including the classification, description and analysis of several of the main models developed on the subject.

Classification of the models

The combustion system hearth is usually divided into two zones according to the phase present: the solid zone or bed and the gaseous zone or freeboard. These can be modeled independently or together according to the complexity and objectives of the simulation, leading to the development of different types of models for different systems and conditions. The classification of solid biomass combustion models varies slightly according to the author consulted. A widely accepted classification is presented by Karim and Naser [12], who categorize the models according to the way the energy equation is calculated, as shown in Table I.

Table 1. Classification of biomass combustion models [12]

Model type	Description
Homogeneous	It is assumed that the gas and solid phases have the same temperature, so a single balance equation is applied. It is not recommended because the phases have very different temperatures.
Heterogeneous	Each phase (solid and gas) has its own balance equations. They are divided into: * Continuous: They treat the two phases as if they were continuously distributed throughout the domain. Its restriction is that inter-particle effects cannot be adequately described. * Discrete particle: The bed is considered as an assembly of representative particles, where each of them undergoes a process of thermal conversion.

Source: Own elaboration

According to Yang et al. [16] the models can be categorized into "thermally thick" or "thermally thin" according to the value of the Biot number in the bed, in the first case ($Bi>>1$) large temperature gradients are reached within the particles leading to superposition of the combustion stages (drying, pyrolysis and char combustion) and in the second case ($Bi<2$) the intra-particle effects are neglected and the stages are assumed to occur consecutively throughout the particle.

Dernbecher et al [10] classify the models, according to the approach used for the treatment of boundary conditions, into four categories: empirical, separated bed, porous zone and discrete particle. These are described below.

Empirical Approach

This approach consists of simulating the freeboard taking into account the input of gases from the bed without the need for coupling with a solid phase combustion model, the bed is usually divided into four sections corresponding to the three stages of combustion (drying, pyrolysis and combustion of the carbonaceous phase) and the remaining ashes, and the profiles of temperature, mass flow and concentration of gaseous species are determined entirely experimentally or are calculated from the elemental composition of the biomass. In the first case, pyrolysis experiments are performed to determine the volatiles released from the fuel at a certain temperature; the conditions of these experiments differ from the conditions during combustion, since they are carried out at low temperatures and the presence of oxygen is neglected [17]. In the second case, calculations based on experimental data are used to give information about combustible gases, which some authors call the semi-empirical approach. The empirical approach is easy to implement and represents low computational effort so, when one wants to simulate an already measured system, it can be the best approach [10]; however it is not flexible to changes making it have low capacity to predict combustion in the design phase [15]. One type of application for this approach is the improvement of combustor designs for certain operating conditions in an existing combustion system [10]. Flexibility improves when working with semi-empirical models, however they need specific data that must be assumed if they are not known, which affects their predictive capability.

Separate bed or "Stand Alone" approach

In this approach, independent models are used for the bed and the freeboard, which are coupled in one or two directions. Generally, the simulation of the gas phase is performed by means of a commercial CFD code, while for the solid phase an independent model is developed where drying, pyrolysis and char consumption in the bed are simulated. This is the most widely used approach, by means of which zero-dimensional, one-dimensional, two-dimensional and three-dimensional models have been developed, although this last type is rare, generally the three-dimensional models are developed under the porous zone approach. These are more flexible models than the empirical ones and represent a low computational consumption, they are mainly used in systems with bulk fuel bed and continuous operation such as pellet boilers or systems with moving grate [10].

Porous zone approach

It is the evolution of the separated bed approach, the bed is modeled as a porous medium, which allows air to flow through it, considering heat and mass exchange between the gas and solid phases. The necessary parameters for the properties of the porous medium are taken from measurements. The bed and freeboard are simulated in the same domain. This is the approach used by several commercial software, in which case it is necessary to use user-defined functions (UDF) to jointly solve the bed and freeboard due to the complexity of the thermal conversion in the solid phase. This approach is more reliable than the previous ones in terms of bed independence and extensibility, however it is more complicated and requires more computational time.

Discrete Particle Method (DPM) Approach

In this approach the biomass particles are represented by Lagrangian particles whose trajectory is calculated based on the forces applied to them. The thermo-chemical conversion of each fuel particle is calculated individually. It is an approach that allows a detailed description of the fuel particles in the bed model, however computationally expensive. It is used to simulate fuel beds with bulk material such as wood chips or pellets.

Table 2 presents several of the most relevant works on solid biomass combustion modeling developed in the last 20 years, where their classification according to the mentioned approaches, the type of system and biomass for which they were developed, the parameters obtained from the simulation and the software used to support it are shown. As can be seen, the four approaches have been successfully used in recent years, which indicates that all four remain valid; the selection of the approach to be used depends on the objective of the simulation and the system to be modeled. In most of the works, commercial software is used, which is used to model the gas phase of the hearth (freeboard) and sometimes the bed; in the latter case, the use of UDFs is necessary to expand the CFD capacity. It can also be observed that, generally, simulation is used to obtain temperatures, flow velocities and process emissions, this is due to the fact that the performance of the system is studied at different conditions and these values allow determining indicators for this purpose. The performance of a packed bed boiler can be determined by means of thermal conversion efficiency and emissions, the former expressed through the burn rate, ignition velocity, peak temperature and thickness of the reaction zone; while the latter is constituted by particulate (soot, organic particles and ash particles) and gaseous (H_2O, CO, CO_2, CH_4, NO_x and other hydrocarbons) emissions [15].

In Colombia, few works have been presented on the subject, which simulate the combustion of sugar cane bagasse. For example, the works of Mendieta and Sanchez [18], Guevara [19], Diaz et al. [20] and Correa [21], in the first two, combustion was simulated in Ward-Cimpa combustion chambers used in the production of panela, in the first a one-dimensional mathematical model was used and in the second a two-dimensional model, in the remaining works an industrial boiler was simulated, dividing it into three parts: primary air circuit, secondary air circuit and the furnace. Further details of these works are presented in Table II.

Main applications of the full simulation models

The comprehensive simulation models are those that focus on simulating the complete combustion system and not only in a sub-process of combustion, they usually use global reaction schemes with few reactions to reduce the computational cost. They are models that have been mainly used to simulate combustion in: mobile grate systems, pellet boilers, wood stoves and straw bales [10]. A brief description of each is presented below.

Mobile grid systems

Combustion system fireplaces can be classified into static and dynamic, within the latter are the mobile grate fireplaces [2], which are the most used for combustion at industrial level [15]; covering a wide range of powers, ranging from 240 kW to 108 MW. For this reason most of the publications on biomass combustion modeling are related to this application. The models are generally developed under the empirical, two-dimensional separated bed and discrete particle approaches, aiming to predict hearth temperatures and emissions of NO_x, CO, ash and other pollutants. The most commonly used fuels have been: municipal solid waste, wood chips and straw [10].

Pellet boilers

Static-fired pellet boilers (fixed grate) are widely used in small to medium scale applications, ranging from 8 to 250 kW [10]. There are similarities between small scale and industrial scale combustion because of the small horizontal gradients, which means that small scale boilers are often used to understand the process carried out in moving bed boilers [15]. The most commonly applied approaches for CFD simulation of these systems are the empirical and porous zone approaches.

Table 2. Description of models developed in recent years

Author	Year	Focus	Thermal regime	Combuster Type	Fuel	Parameters obtained from simulation	Software
Knaus et al. [22]	2000	Empirical	N/A	Wood stove	Wooden logs	Speed, temperature and composition of gases at different points, in order to study the effects of mixing conditions, air distribution and geometry on performance.	AIOLOS
Cooper and Hallett [23]	2000	Stand Alone (1D)	Thermally thin	Fixed Grill	Carbon particles	Bed temperature and volumetric fraction of gases at different air ratios and fuel characteristics.	NI
Peters [24]	2002	DPM	Thermally thick	Mobile Grill	Spruce wood spheres	Variation of the mass of the particles against time for the three stages of combustion.	N/A
Thunman and Leckner [25]	2002	Stand Alone (1D)	Thermally thick	Fixed Grill	Wood Chips	Thickness of the reaction front.	NI
Yang et al. [26]	2002	Stand Alone (2D)	Thermally thin	Fixed Grill (Movable bed)	Municipal solid waste	Temperature distribution, waste composition and gas species.	Software FLIC (Own creation)
Bruch et al. [27]	2003	DPM	Thermally thick	Fixed Bed Reactor	Beech wood spheres	Variation in particle mass and bed height over time.	N/A
Eskilsson et al. [28]	2004	Empirical	N/A	Reactor tube	Pellets (characterized in paper)	Temperature, air stoichiometry, combustion status and the division between NH_3 and HCN.	Chemkin
Kær and Søren[29]	2004	Stand Alone (2D)	Thermally thin	Mobile Grill	Straw	Emissions, char distribution in the bed, temperature and speed profiles and heat flows in the home.	CFX
Miltner et al. [30]	2006	Porous Zone	Thermally thin	Whole bale combustion chamber	Bale of whole hue	Emissions and distribution of speeds and temperatures in the chamber.	RANS-CFD-solver FLUENT
Galgano et al. [31]	2006	Stand Alone (1D)	Thermally thick	Wooden log furnace	Individual wood trunk	Variation of the solid mass fraction, mass loss rate and temperature at various points over time.	CFX 4.4

Author	Year	Focus	Thermal regime	Combuster Type	Fuel	Parameters obtained from simulation	Software
Porteiro et al. [32]	2009	Stand Alone (1D)	Thermally thick	Fixed Grill	Wood pellets	Temperature distribution, CO and trajectory of char particles.	ANSYS Fluent
Djurovi'c et al. [33]	2012	Empirical	N/A	Fixed Grill (piston fed)	Soya straw bales	Temperature distribution, speed and CO concentration in the boiler.	FLUENT 6.3.26
Gómez et al. [34]	2012	Porous Zone	Thermally thin	Fixed Grill	Pellets (characterized in paper)	Heat transfer, temperature and species (gas) concentration	ANSYS Fluent
Chaney et al. [14]	2012	Porous Zone	Thermally thin	Fixed Grill	Wood pellets	Temperature distribution, speed, O_2, CO and volatile species.	ANSYS Fluent
Collazo et al. [35]	2012	Porous Zone	Thermally thin	Fixed Grill	Wood pellets	Temperature distribution of gases and emissions.	ANSYS Fluent
Gómez et al. [13]	2013	Porous Zone	Thermally thin	Combustion Tube	Wood pellets	Solid temperature, gas temperature, solid fraction, particle diameter and fuel density; for different air flows over time.	ANSYS Fluent
Haller et al. [36]	2013	Empirical	N/A	Fixed Grill	Wood pellets	Temperature and speed distribution.	OpenFoam
Mendieta y Sanchez [18]	2014	Stand Alone (1D)	Thermally Thin	Fixed Grill	Sugar cane bagasse	Combustion rate, bed temperature and volumetric fraction of CO, O_2 and CO^2 as a function of the mass fraction of humidity.	N/A
Guevara [19]	2014	Porous Zone	Thermally Thin	Fixed Grill	Sugar cane bagasse	Temperature profiles of particles and gases at different percentages of excess primary and secondary air. Mass fractions of O_2 and CO in different positions in the chamber.	ANSYS Fluent
Bhuiyan y Naser [37]	2015	Stand Alone (3D)	Thermally thin	Co-firing	Irregular biomass + Brown Coal	Temperature, airflow and emissions for various fuel mixtures (biomass and coal).	AVL Fire
Gómez et al. [38]	2015	Porous Zone	Thermally thick	Combustion Tube	Wood pellets	Temperature evolution in the center and borders of the tube, particle mass change, bed and freeboard temperature profiles, and particle diameter change, for different air flows.	ANSYS Fluent
Mahmoudi et al. [39]	2016	DPM	Thermally thick	Mobile Grill (validated with a fixed bed reactor)	Wood Chips	Temperature and species distribution in the home.	N/A
Cordiner et al. [40]	2016	Stand Alone (3D)	Thermally thin	Fixed Grill (Fixed bed)	Grape bagasse and wood chips	Temperature distribution, H_2O content, particle diameter and velocity fields.	Open-foam
Buchmayr et al. [41]	2016	Semi-empirical	N/A	Reactor equipped with “enhanced air staging”	Softwood chips	Temperature distribution and concentrations of O_2, OH and CO The values obtained with the SFM and EDC combustion models were compared.	ANSYS Fluent
Silva et al. [42]	2017	Empirical	N/A	Fixed Grill	Forest residues	Temperature, speed and species concentration fields in the burner, for different air mixtures with combustion gases.	ANSYS Fluent
Gómez et al. [43]	2017	Porous Zone	Thermally thick	Fixed Grill	Wood pellets	Heat transferred to water, temperature profiles and gas composition The Thermally Thick and Thermally Thin approaches were compared.	ANSYS Fluent
Mätzing et al. [44]	2018	Stand Alone (1D)	Thermally thin	Fixed Bed Reactor	Wood chips, solid recovered fuels and blends.	Ignition delay, ignition rate, ignition front velocity and mass conversion rate The influence of the initial conditions on these magnitudes is studied.	ANSYS Fluent
García [2]	2018	Porous Zone	NI	Fixed Grill (Fixed bed)	Wood pellets	NI	ANSYS Fluent
Buchmayr et al. [45]	2018	Semi-empirical	N/A	Fixed Grill, equipped with “extreme-air-staging”	Spruce wood stem (Picea abies) with bark	CO and OH emissions, velocity and temperature distribution, The values obtained with the SFM and EDC combustion models were compared.	ANSYS Fluent

Author	Year	Focus	Thermal regime	Combuster Type	Fuel	Parameters obtained from simulation	Software
Díaz et al. [20]	2018	DPM	N/A	Fixed Grill	Sugar cane bagasse	Distribution of speed, temperature and emissions.	ANSYS Fluent
Correa [21]	2018	DPM	N/A	Fixed Grill	Sugar cane bagasse	Temperature distribution, O_2 and pollutant emissions	ANSYS Fluent
Karim y Naser [46]	2018	Porous Zone	Thermally Thin	Mobile Grill	Mixture of wood chips, bark and saw dust produced in a sawmill with a high moisture content	Temperature distribution, densities and concentration of species in the home The effect of primary air was studied.	AVL Fire
Karim y Naser [47]	2018	Porous Zone	Thermally thin	Combustible tube	Wood pellets, poplar pellets, olive stone and pine chips	Bed height over time, gas and solid temperature profiles, solid and O_2 fraction, particle diameter and density of char and wet and dry solid. Air and fuel type were varied.	AVL Fire
Gómez et al. [48]	2019	Porous Zone	Thermally Thin	Fixed Grill	Pine wood pellets	Heat obtained by the boiler and emission of pollutants at different values of recirculation gases (EGR).	ANSYS Fluent

N/A: Not Applicable and NI: No information presented.
Source: Own elaboration.

Mobile grate boilers are the most widely used industrially [15], however, low-power fixed-bed boilers have gained popularity in recent years due to their simplicity, low operating cost and low requirements in terms of fuel preparation and transportation [15], [41], [49]. This is an advantage for developing countries because this type of boilers, fueled by local waste, can be used for power generation in remote areas [50], [51], while in industrialized countries their benefit is observed in both district heating and electricity supply [52]. The European market for small-scale power plants below 20 MWth is expected to grow by 100% in the next decade and growth rates are expected to be high worldwide [44]. Although this technology is well developed, improvements in low power biomass boilers are required to reduce their pollutant emissions and increase their efficiency [41], [45], [53], [54].

Wood-burning stoves

With a power of about 32 kW, they are mainly used for domestic heating [10]. The following approaches are generally used to model them: empirical, one-dimensional separated bed and porous zone.

Straw bales

This application is the least common of all, mainly the empirical and porous zone approaches have been used.

Conclusions

A review of the state of the art of CFD modeling of solid biomass combustion in the last 20 years worldwide was conducted, presenting the approach, objectives and application of several relevant models from the mentioned period.

A review of the state of the art of CFD modeling of solid biomass combustion in the last 20 years worldwide was performed, presenting the approach, objectives and application of several relevant models of the mentioned period.

Solid biomass combustion modeling is a complex process due to the large number of sub-models and computational resources it demands. In the vast majority of the works, commercial CFD software is used to simulate the hearth freeboard, while the bed requires the implementation of user-defined functions because commercial software does not have the capability to simulate it independently.

Combustion models can be classified, according to the way the energy equation is calculated, into homogeneous and heterogeneous, of which the former have not presented good results because they assume the same temperature for the two hearth phases, which is why the current models are developed from the second point of view. Regarding the modeling approach, the models can be empirical, separate bed, porous zone or discrete particle models, which are used according to the objectives and system to be modeled. The separated bed approach has been the most widely used because of its flexibility and relatively low computational cost.

The main applications for combustion models are: mobile grate systems, pellet boilers, wood stoves and straw bales; of which the first one is the most studied because it is the most related to industrial systems. The empirical approach has been used in all applications because it is the easiest to implement and requires less computational effort.

Few articles have been published in Colombia on the subject, which have focused on the combustion of sugar cane bagasse.

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References

[1] International Organization for Standardization, “ISO 16559:2014. Solid biofuels -Terminology, definitions and descriptions”. Disponible en: http://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/71/57111.html.

[2] R. García-Fernández, “Modelización cinética y optimización de parámetros de combustión en calderas de biomasa”, Doctorado, *Universidad de Oviedo*, España, 2014.

[3] A. Álvarez-Rodríguez, “Kinetic and fluiddynamic modeling of a biomass combustor”, *Universidad de Oviedo*, España, 2018.

[4] A. A. Bhuiyan, Md. R. Karim and J. Naser, “Chapter 11 - Modeling of Solid and Bio-Fuel Combustion Technologies”, *Thermofluid Modeling for Energy Efficiency Applications*, M. M. K. Khan y N. M. S. Hassan, Eds. Academic Press, pp. 259-309, 2016.

[5] J. M. F. F. Oro, “Técnicas numéricas en ingeniería de fluidos: introducción a la dinámica de fluidos computacional (CFD) por el método de volúmenes finitos”, *Editorial Reverté*, 2012.

[6] K. Szemmelveisz, I. Szűcs, Á. B. Palotás, L. Winkler and E. G. Eddings, “Examination of the combustion conditions of herbaceous biomass”, *Fuel Processing Technology*, vol. 90, no. 6, pp. 839-847, 2009. Doi: 10.1016/j.fuproc.2009.03.001.

[7] Y. B. Yang, V. N. Sharifi and J. Swithenbank, “Effect of air flow rate and fuel moisture on the burning behaviours of biomass and simulated municipal solid wastes in packed beds”, *Fuel*, vol. 83, no. 11, pp. 1553-1562, 2004. Doi: 10.1016/j.fuel.2004.01.016.

[8] G. F. García Sánchez, J. L. Chacón Velasco and A. Chaves Guerrero, “Modelado de la combustión en motores Diésel: revisión del estado del arte”, *Revista ION*, vol. 26, no. 1, 2013. [En línea]. Disponible

en: http://revistas.uis.edu.co/index.php/revistaion/article/view/3506.

[9] H. Versteeg and W. Malalasekera, "An Introduction to Computational Fluid Dynamics: The Finite Volume Method", *Edición: 2nd rev. ed. Harlow*, England ; New York: Prentice Hall, 2007.

[10] A. Dernbecher, A. Dieguez-Alonso, A. Ortwein and F. Tabet, "Review on modelling approaches based on computational fluid dynamics for biomass combustion systems", *Biomass Conversion and Biorefinery*, vol. 9, no. 1, pp. 129-182, 2019. Doi: 10.1007/s13399-019-00370-z

[11] M. Á. G. Rodríguez, "Contribuciones al desarrollo de un modelo de simulación de combustión de sólidos", *Universidade de Vigo, España*, 2014. http://purl.org/dc/dcmitype/Text

[12] Md. R. Karim and J. Naser, "Progress in Numerical Modelling of Packed Bed Biomass Combustion", *19th Australasian Fluid Mechanics Conference*. Melbourne, 2014.

[13] M. A. Gómez, J. Porteiro, D. Patiño and J. L. Míguez, "CFD modelling of thermal conversion and packed bed compaction in biomass combustion", *Fuel*, vol. 117, pp. 716-732, 2014. Doi: 10.1016/j.fuel.2013.08.078.

[14] J. Chaney, L. Hao and L. Jinxing, "An overview of CFD modelling of small-scale fixed-bed biomass pellet boilers with preliminary results from a simplified approach – ScienceDirect", *Energy Conversion and Management*, vol. 63, pp. 149–156, 2012.

[15] H. Khodaei, Y. M. Al-Abdeli, F. Guzzomi and G. H. Yeoh, "An overview of processes and considerations in the modelling of fixed-bed biomass combustion", *Energy*, vol. 88, pp. 946-972, 2015. Doi: 10.1016/j.energy.2015.05.099.

[16] Y. B. Yang, V. N. Sharifi and J. Swithenbank, "Numerical Simulation of the Burning Characteristics of Thermally-Thick Biomass Fuels in Packed-Beds", *Process Safety and Environmental Protection*, vol. 83, no. 6, pp. 549-558, 2005, Doi: 10.1205/psep.04284.

[17] H. Thunman, F. Niklasson, F. Johnsson and B. Leckner, "Composition of Volatile Gases and Thermochemical Properties of Wood for Modeling of Fixed or Fluidized Beds", *Energy Fuels*, vol. 15, no. 6, pp. 1488-1497, 2001. Doi: 10.1021/ef010097q.

[18] O. Mendieta and Z. Sanchez, "Ajuste de un modelo matemático para la combustión de bagazo de caña en una cámara Ward-Cimpa", *Ciencia y Tecnología Agropecuaria*, vol. 15, no. 2, pp. 133-151, 2014.

[19] J. I. Guevara Enciso, "Modelo computacional de la combustión del bagazo de caña en una cámara de combustión tipo ward-cimpa de una hornilla panelera", *Maestría, Universidad de los Andes*, 2014.

[20] F. A. Diaz-Mateus, H. C. Alvarez-Castro, A. Chaves-Guerrero, F. A. Diaz-Mateus, H. C. Alvarez-Castro and A. Chaves-Guerrero, "CFD simulation of sugarcane bagasse combustion in an industrial grate boiler", *DYNA*, vol. 85, no. 204, pp. 169-176, 2018. Doi: 10.15446/dyna.v85n204.65601.

[21] W. R. Correa Vargas, "Evaluación de la eficiencia de combustión del bagazo de caña en una caldera industrial usando dinámica computacional de fluidos", *Pregrado, Universidad Industrial de Santander*, 2018.

[22] H. Knaus, S. Richter, S. Unterberger, U. Schnell, H. Maier and K. R. G. Hein, "On the application of different turbulence models for the computation of fluid flow and combustion processes in small scale

wood heaters", *Experimental Thermal and Fluid Science*, vol. 21, no. 1, pp. 99-108, 2000. Doi: 10.1016/S0894-1777(99)00059-X.

[23] J. Cooper and W. L. H. Hallett, "A numerical model for packed-bed combustion of char particles", *Chemical Engineering Science*, vol. 55, no. 20, pp. 4451-4460, 2000. Doi: 10.1016/S0009-2509(00)00097-X.

[24] B. Peters, "Measurements and application of a discrete particle model (DPM) to simulate combustion of a packed bed of individual fuel particles", *Combustion and Flame*, vol. 131, no. 1, pp. 132-146, 2002. Doi: 10.1016/S0010-2180(02)00393-0.

[25] H. Thunman and B. Leckner, "Co-current and counter-current fixed bed combustion of biofuel—a comparison☆", *Fuel*, vol. 82, no. 3, pp. 275-283, 2003. Doi: 10.1016/S0016-2361(02)00289-2.

[26] Y. B. Yang, Y. R. Goh, R. Zakaria, V. Nasserzadeh and J. Swithenbank, "Mathematical modelling of MSW incineration on a travelling bed", *Waste Management*, vol. 22, no. 4, pp. 369-380, 2002. Doi: 10.1016/S0956-053X(02)00019-3.

[27] C. Bruch, B. Peters and T. Nussbaumer, "Modelling wood combustion under fixed bed conditions☆", *Fuel*, vol. 82, no. 6, pp. 729-738, 2003. Doi: 10.1016/S0016-2361(02)00296-X.

[28] D. Eskilsson, M. Rönnbäck, J. Samuelsson and C. Tullin, "Optimisation of efficiency and emissions in pellet burners", *Biomass Bioenergy*, vol. 27, no. 6, pp. 541-546, 2004. Doi: 10.1016/j.biombioe.2003.09.008.

[29] S. K. Kær, "Numerical modelling of a straw-fired grate boiler", *Fuel*, vol. 83, no. 9, pp. 1183-1190, 2004, Doi: 10.1016/j.fuel.2003.12.003.

[30] M. Miltner, A. Miltner, M. Harasek and A. Friedl, "Process simulation and CFD calculations for the development of an innovative baled biomass-fired combustion chamber", *Applied Thermal Engineering*, vol. 27, no. 7, pp. 1138-1143, 2007. Doi: 10.1016/j.applthermaleng.2006.02.048.

[31] A. Galgano, C. Di Blasi, A. Horvat and Y. Sinai, "Experimental Validation of a Coupled Solid- and Gas-Phase Model for Combustion and Gasification of Wood Logs", *Energy Fuels*, vol. 20, no. 5, pp. 2223-2232, 2006. Doi: 10.1021/ef060042u.

[32] J. Porteiro, J. Collazo, D. Patiño, E. Granada, J. C. Moran Gonzalez and J. L. Míguez, "Numerical Modeling of a Biomass Pellet Domestic Boiler", *Energy Fuels*, vol. 23, no. 2, pp. 1067-1075, 2009. Doi: 10.1021/ef8008458.

[33] D. Djurović, S. Nemoda, D. Dakić, M. Adzić and B. Repić, "Furnace for biomass combustion – Comparison of model with experimental data", *International Journal of Heat and Mass Transfer*, vol. 55, no. 15, pp. 4312-4317, 2012. Doi: 10.1016/j.ijheatmasstransfer.2012.03.079.

[34] M. Gómez, R. Comesaña, M. A. Álvarez Feijoo and P. Eguía, "Simulation of the Effect of Water Temperature on Domestic Biomass Boiler Performance", *Energies*, vol. 5, pp. 1044-1061, 2012. Doi: 10.3390/en5041044.

[35] J. Collazo, J. Porteiro, J. L. Míguez, E. Granada and M. A. Gómez, "Numerical simulation of a small-scale biomass boiler", *Energy Conversion and Management*, vol. 64, pp. 87-96, 2012. Doi: 10.1016/j.enconman.2012.05.020.

[36] J. Haller, I. Hartmann, M. König and A. Ortwein, "Basic studies on the development of micro combustion systems for biomass", *Proceedings of the European Combustion Meeting, Lund University, Suecia*, 2013. https://www.researchgate.net/publication/256715286.

[37] A A. Bhuiyan and J. Naser, "CFD modelling of co-firing of biomass with coal under oxy-fuel combustion in a large scale power plant", *Fuel*, vol. 159, pp. 150-168, 2015. Doi: 10.1016/j.fuel.2015.06.058.

[38] M. A. Gómez, J. Porteiro, D. Patiño and J. L. Míguez, "Fast-solving thermally thick model of biomass particles embedded in a CFD code for the simulation of fixed-bed burners", *Energy Conversion and Management*, vol. 105, pp. 30-44, 2015. Doi: 10.1016/j.enconman.2015.07.059.

[39] A. H. Mahmoudi, X. Besseron, F. Hoffmann, M. Markovic and B. Peters, "Modeling of the biomass combustion on a forward acting grate using XDEM", *Chemical Engineering Science*, vol. 142, pp. 32-41, 2016. Doi: 10.1016/j.ces.2015.11.015.

[40] S. Cordiner, V. Mulone, A. Manni and V. Rocco, "Biomass furnace study via 3D numerical modeling", *International Journal of Numerical Methods for Heat & Fluid Flow*, vol. 26, no. 2, pp. 515-533, 2016. Doi: 10.1108/HFF-03-2015-0089.

[41] M. Buchmayr, J. Gruber, M. Hargassner and C. Hochenauer, "A computationally inexpensive CFD approach for small-scale biomass burners equipped with enhanced air staging", *Energy Conversion and Management*, vol. 115, pp. 32-42, 2016. Doi: 10.1016/j.enconman.2016.02.038.

[42] J. Silva, J. Teixeira, S. Teixeira, S. Preziati and J. Cassiano, "CFD Modeling of Combustion in Biomass Furnace", *Energy Procedia*, vol. 120, pp. 665-672, 2017. Doi: 10.1016/j.egypro.2017.07.179.

[43] M. A. Gómez, J. Porteiro, D. De la Cuesta, D. Patiño and J. L. Míguez, "Dynamic simulation of a biomass domestic boiler under thermally thick considerations", *Energy Conversion and Management*, vol. 140, pp. 260-272, 2017. Doi: 10.1016/j.enconman.2017.03.006.

[44] H. Mätzing, H.-J. Gehrmann, H. Seifert and D. Stapf, "Modelling grate combustion of biomass and low rank fuels with CFD application", *Waste Management*, vol. 78, pp. 686-697, 2018. Doi: 10.1016/j.wasman.2018.05.008.

[45] M. Buchmayr, J. Gruber, M. Hargassner and C. Hochenauer, "Performance analysis of a steady flamelet model for the use in small-scale biomass combustion under extreme air-staged conditions", *Journal of the Energy Institute*, vol. 91, no. 4, pp. 534-548, 2018. Doi: 10.1016/j.joei.2017.04.003.

[46] Md. R. Karim and J. Naser, "CFD modelling of combustion and associated emission of wet woody biomass in a 4 MW moving grate boiler", *Fuel*, vol. 222, pp. 656-674, 2018. Doi: 10.1016/j.fuel.2018.02.195.

[47] Md. R. Karim and J. Naser, "Numerical study of the ignition front propagation of different pelletised biomass in a packed bed furnace", *Applied Thermal Engineering*, vol. 128, pp. 772-784, 2018. Doi: 10.1016/j.applthermaleng.2017.09.061.

[48] M. A. Gómez, R. Martín, S. Chapela and J. Porteiro, "Steady CFD combustion modeling for biomass boilers: An application to the study of the exhaust gas recirculation performance", *Energy Conversion*

and Management, vol. 179, pp. 91-103, 2019. Doi: 10.1016/j.enconman.2018.10.052.

[49] C. Yin, L. A. Rosendahl and S. K. Kær, “Grate-firing of biomass for heat and power production”, *Progress in Energy and Combustion Science*, vol. 34, no. 6, pp. 725-754, 2008. Doi: 10.1016/j.pecs.2008.05.002.

[50] G. M. Faé Gomes, A. C. Faria Vilela, L. D. Zen and E. Osório, “Aspects for a cleaner production approach for coal and biomass use as a decentralized energy source in southern Brazil”, *Journal of Cleaner Production*, vol. 47, pp. 85-95, 2013. Doi: 10.1016/j.jclepro.2012.09.037.

[51] Y. S. Mohammed, A. S. Mokhtar, N. Bashir and R. Saidur, “An overview of agricultural biomass for decentralized rural energy in Ghana”, *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 15-25, 2013. Doi: 10.1016/j.rser.2012.11.047.

[52] C. Bang-Møller, M. Rokni, B. Elmegaard, J. Ahrenfeldt and U. B. Henriksen, “Decentralized combined heat and power production by two-stage biomass gasification and solid oxide fuel cells”, *Energy*, vol. 58, pp. 527-537, 2013. Doi: 10.1016/j.energy.2013.06.046.

[53] M. Buchmayr, J. Gruber, M. Hargassner and C. Hochenauer, “Spatially resolved chemical species concentrations above the fuel bed of a small grate-fired wood-chip boiler”, *Biomass Bioenergy*, vol. 95, pp. 146-156, 2016. Doi: 10.1016/j.biombioe.2016.10.004.

[54] M. Buchmayr, J. Gruber, M. Hargassner and C. Hochenauer, “Experimental investigation of the primary combustion zone during staged combustion of wood-chips in a commercial small-scale boiler”, *Biomass Bioenergy*, vol. 81, pp. 356-363, 2015. Doi: 10.1016/j.biombioe.2015.07.016.