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# Dynamic simulation of a biomass domestic boiler under thermally thick considerations

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ABSTRACT

A biomass combustion model with a thermally thick approach is presented and applied to the simulation of a commercial biomass domestic boiler. A subgrid scale model is used to divide the particles into several grid points, each representing one of the different combustion stages. These grid points determine the variables of the solid phase located in the packed bed calculated as a porous zone with a volume-averaged approach. The combustion model is coupled with a fuel-feeding model based on Lagrangian trajectories of particles. Those are transformed into solid phase variables as soon as they reach the packed bed, allowing the numerical model to simulate the transient behavior of such a system. This methodology is here applied to a 27-kW boiler operating in stable conditions with two feeding systems: one in which the particle feeding rate is kept constant in time and another in which the feeding rate varies randomly through time. The behavior of such a boiler is better understood thanks to the completeness of the model here presented, whose results are also compared to experimental measurements. The CFD model gives reasonably good predictions of the heat transferred, the flue gas temperature, the excess air coefficient and $CO_2$ emissions, as well as the fluctuations of the boiler when the feeding rate is not constant. However, the model underestimates unburnt species like CO, probably due to the oversimplified gas reaction mechanisms employed in the simulation.



## 1. Introduction

The interest in renewable energy sources in the latest decades is causing new improvements in biomass combustion systems. One of these improvements is the numerical modelling and simulation of combustion devices such as boilers, burners and furnaces, which allows testing different geometries and operating conditions with reasonably low costs during their design and development phase.

Computational Fluid Dynamics (CFD) has become an useful tool to simulate combustion systems since it is highly developed in the modelling of flow, turbulence, heat transfer, and species transport and reaction. An important number of CFD works about different combustion phenomena were presented during the last decade. Processes such as combustion in gas furnaces [1–3], oxy-fuel combustion [4,5], heat transfer effects under combustion conditions [6,7], pulverized coal combustion [8–10], spray combustion [11] were simulated using CFD with reasonably successful results. However, the interaction of flow with solid particles of biomass and the thermochemical conversion of these particles is a complex process still in the need of further investigation.

A wide variety of strategies has been proposed in the literature to address the complex phenomena involved in bed reactions, from simple heat and mass balances to unsteady three-dimensional models. A complete overview about biomass combustion was presented by Khodaei et al. [12] and Karim and Naser [13]. The simplest way of simulating combustion is by introducing the combustion products directly as a boundary condition. Eskilsson et al. [14] used this method to introduce the composition and gas properties based in experimental measurements. Nonetheless, this method is severely limited by the lack of generalizability to any combustion operating conditions other than the ones used during the empirical tests performed. A simple but efficient model for small packed beds is used by Collazo et al. [15] and Gómez et al. [16], based on mass and energy balances in a nondimensional bed computational volume to calculate the mass of gases, power and species generated in the combustion. Porteiro et al. [17] also used a zero-dimensional transient model that takes into account the continuous contribution of particles of different sizes within the bed. One-dimensional bed models are common to simulate boilers

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**Nomenclature**

| | |
|---|---|
| $a$ | linear equation coefficient ($W\,K^{-1}$ in the energy equation), ($s^{-1}$ in the volume equation) |
| $A_f$ | area of the face f ($m^2$) |
| $b$ | linear equation independent coefficient (W in the energy equation), ($m^3\,s^{-1}$ in the volume equation) |
| $C_p$ | specific heat ($J\,kg^{-1}\,K^{-1}$) |
| $h$ | solid phase enthalpy ($J\,kg^{-1}$) |
| $k$ | thermal conductivity ($W\,m^{-1}\,K^{-1}$) |
| $LH$ | latent heat of evaporation ($J\,kg^{-1}$) |
| $r$ | radius (m) |
| $R$ | layer radius (m) |
| $S$ | source term ($W\,m^{-3}$ in the energy equation), ($m^3\,s^{-1}$ in the volume equation) |
| $T$ | temperature (K) |
| $t$ | time (s) |
| $v$ | velocity of the solid phase ($m\,s^{-1}$) |
| $V$ | volume ($m^3$) |
| $Y$ | mass fraction (–) |

*Greek*

| | |
|---|---|
| $\varepsilon$ | solid fraction (–) |
| $\rho$ | density ($kg\,m^{-3}$) |
| $\dot{\omega}'''_i$ | generation or consumption rates of the wood component i ($kg\,m^{-3}\,s^{-1}$) |
| $\dot{\omega}'''_{V_{part}}$ | consumption rate of the particle volume ($m^{-3}\,s^{-1}$) |
| $\psi$ | particle sphericity (–) |

*Subscripts*

| | |
|---|---|
| $CC$ | central cell |
| E | external layer |
| $evap$ | evaporation |
| $f_j$ | j-th face of a cell |
| $h$ | enthalpy |
| $I$ | internal layer |
| $I,I$ | interior of the internal layer |
| $moist$ | moisture |
| max | maximum |
| $NC$ | neighbor cell |
| $P$ | current layer |
| $part$ | particle |
| s | solid phase |
| $T$ | total |
| $V$ | volume |

*Superscripts*

| | |
|---|---|
| 0 | variable in the previous time step |

with the bed located along a grate (also dubbed grate furnaces). Authors such as Yin et al. [18], Kaer [19] and Zhou et al. [20] used the "walking column" approach to model the bed as several columns of biomass with different ratios of wood, char and ashes. These columns represent the steady movement of the particles along the grate. A similar alternative is the model by Cooper and Hallet [21], where combustion advances downwards since the fuel is fed from above the bed. A more complex geometry is found in the work of Yang et al. [22], who used a finite volume method in the bed and solved the conservation equations of the solid phase variables in an additional grid outside from the main CFD computational domain. Collazo et al. [23] simulated a biomass reactor by modelling a three-dimensional packed bed as a porous zone governed by a set of Eulerian variables representing the solid phase. Gómez et al. [24] extended this approach by adding the bed shrinkage submodel and improving the directional resolution of the radiative heat transfer to and from the bed. This method has been already succesfully applied to the transient simulation of two different biomass boilers [25,26] together with fuel-feeding submodels. This approach is useful in order to analyse ignition and the transient regime in combustion that leads to a steady state.

In most of the cited works, a thermally thin approach is used, thus the intraparticle temperature gradients are not considered. A thermally thick approach requires more effort both during the modelling phase and computationally but it is necessary to obtain higher accuracy in the timing of combustion stages. Some works have proposed thermally thick models focused on a single particle. The model by Lu et al. [27] is applicable to different shapes and is able to calculate the combustion stages inside a single particle considering the surroundings as boundary conditions. Babu and Chaurasia [28] discretized the particle in a subgrid with a tridiagonal matrix algorithm to solve the heat transfer. Porteiro et al. [29] also used a subgrid scale for cylindrical discretization. The amount of grid points selected provides good resolution without a significant increase in the computational time. Thunman et al. [30] reduced the number of grid points to the number of combustion stages. Galgano et al. [31] modelled and tested a model for glowing particles exposed to high radiation with special attention to drying and pyrolysis. Some other authors applied single-particle models in sets of particles representing packed beds. Wurzenberger et al. [32] calculated mass, momentum, energy, and species of single particles, validating the model with experimental data from a biomass-fired grate. Peters [33] and Bruch et al. [34] applied a Lagrangian approach with a one-dimensional subgrid inside the particles contained in a Cartesian grid representing the porous bed. Yang et al. [35,36] also used two-dimensional Cartesian grids so that biomass interior, biomass surface or gas cells behave differently. The resolution of this method was further improved in [36] by using a double mesh inside the solid phase to represent both solid and gas fractions. The approach proposed by Thunman in [30] was used by Mehrabian et al. [37,38] and Ström and Thunman [39,40] in transient models combined with the multiphysics of the Eulerian porous beds. The authors' previous paper [41] also used the thermally thick approach by Thunman [30] to simulate a biomass combustor through an efficient algorithm that solves a large amount of particles in reasonably short calculation times.

In this paper, the thermally thick model proposed by the authors in [41] is improved to operate in the dynamic simulation of a commercial boiler performed through the CFD commercial code ANSYS fluent 16, a feature not so common in the literature due to the large computational effort required. Consequently, a fuel-feeding submodel is introduced here to take into account the dynamics of the arrival of new particles to the packed bed and, thus, to recalculate the variables of the solid phase. The trajectories of these particles are calculated using a Lagrangian approach and are transformed in subgrid Eulerian solid phase variables as soon as they fall onto the packed bed. Two experimental cases are simulated starting from the ignition of the boiler and solved in a transient framework until a quasi-steady state is reached, which is in fact the same methodology employed in the experiments. The main variables of the model will be shown and the behavior of the boiler is analyzed and compared to experimental tests.