MODELING OF BIOMASS COMBUSTION ON A RECIPROCATING-GRATE SUPER-HEATER

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Abstract

Biomass combustion on a 15.7 MW reciprocating grate is modeled by using two different methods. In the first approach, a Computational Fluid Dynamics (CFD) model of the gaseous reactive flow in the freeboard is coupled to an offline model of the biomass bed, that is treated as a series of perfectly stirred reactors. In the second approach, the eXtended Discrete Element Method (XDEM) is employed to describe the granular behavior of the biomass particles on the moving grate. Results are validated with a few temperature measurements.

Introduction

Modeling biomass combustion on moving grates is very challenging because the multi-phase and multi-species phenomena, involving particles bed motion, turbulence, chemical reactions and the heat radiation, all of them affecting biomass conversion. Different approaches have been proposed and they may be divided in two principal categories: single-phase and multi-phase models. The formers do not directly include the ensemble of moving particles into the computational domain, as only the gas phase in the freeboard is solved directly though CFD (e.g. [1][2]). The biomass bed influence is taken into account by assigning appropriate boundary conditions to the freeboard model. Instead, multi-phase models attempt to model both solid and gaseous phases. These models can be divided into Eulerian-Eulerian models, that treat the ensemble of solid particles as a continuum (e.g. FLIC code [3]) and Eulerian-Lagrangian models, in which the single particles (or cluster of them) are considered individually in their motion and interaction with the others as well as with the gas phase treated in the Eulerian framework (e.g. [4][5]). The main drawback of the Eulerian-Lagrangian models is the high computational cost; depending on the extent of the domain and on the number of particles simulated the time requested for such an approach might become unreasonably long.

The present work wants to investigate limits and potentialities of the two approaches for the numerical modeling of the super-heater of the hybrid “Cornia 2” power plant.

"Cornia2" power plant

The "Cornia 2" power plant belongs to Enel Green Power and is located in the geothermal area of Larderello, in Tuscany. The plant is an example of novel integration between two different renewable resources: geothermal and biomass energy. The recent installation of a biomass-fired super-heater, equipped with a reciprocating grate, has increased the power output of the pre-existing dry steam power station. Here, the geothermal fluid, coming out from the geothermal reservoir in almost dry steam conditions at about 150°C, is super-heated up to 370°C before expanding in the gas turbine. Globally an increase of the net electricity generation from approximately 11.3 MW to 16.5 MW is achieved. The reason for coupling the two resources, instead of installing a separate and pure biomass power plant, is the higher global efficiency of the hybrid design compared to the efficiencies of the two power stations taken independently. The process is depicted in Figure 1.

Currently the plant is operating at nominal conditions for the most of the time and its power output is sufficiently steady. Nonetheless there are still some elements of the plant that could be significantly improved, as for instance: eventually the presence of some unburnt carbon in the bottom ashes; the control and abatement of pollutants, especially NOx; slag formation in the colder zones of the super-heater.

The super-heater (Figure 2) is fueled at a mass flow rate of 5.4 t/h (power thermal input of 15.7 MW) with a mixture of two types of biomass (see Table 1): virgin forest wood-chips and low quality agricultural. The reciprocating grate consists of three independent groups of fixed and moving steps. Primary air (PA) enters from below the grate and is split in six different section, whereas secondary air (SA) is injected straight over the fuel bed through a series of circular nozzles. Flue Gas Recirculation (FGR) is also present.

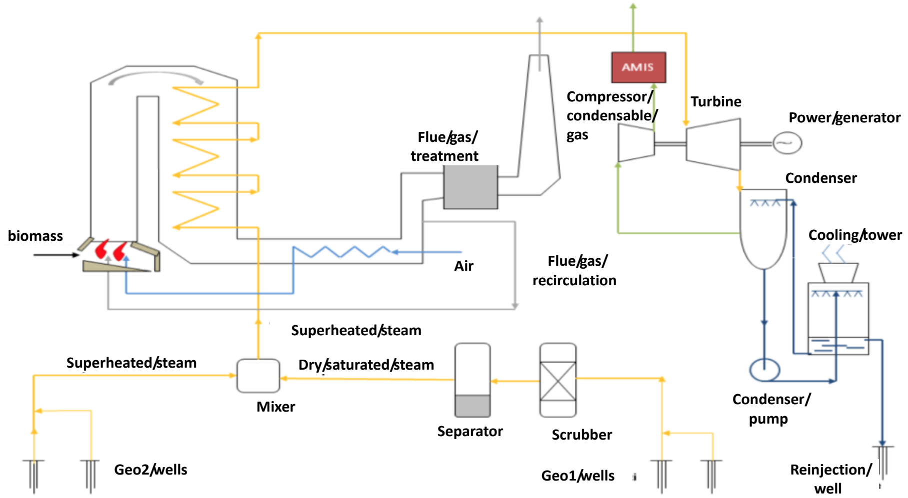

Figure 1. Process flow diagram of “Cornia 2” power plant.

Table 1. Biomass characteristics.

	Mix fraction [%]	Proximate analysis				Ultimate analysis			
		Moisture [%$_{\mathrm{wt,ar}}$]	Volatiles [%$_{\mathrm{wt,ar}}$]	Fixed C [%$_{\mathrm{wt,ar}}$]	Ashes [%$_{\mathrm{wt,ar}}$]	C [%$_{\mathrm{wt,daf}}$]	H [%$_{\mathrm{wt,daf}}$]	O [%$_{\mathrm{wt,daf}}$]	N [%$_{\mathrm{wt,daf}}$]
woodchips	80	34.0	53.7	11.3	1.0	49.60	5.95	44.23	0.22
residues	20	51.0	35.6	8.3	5.1	51.15	6.23	41.67	0.95

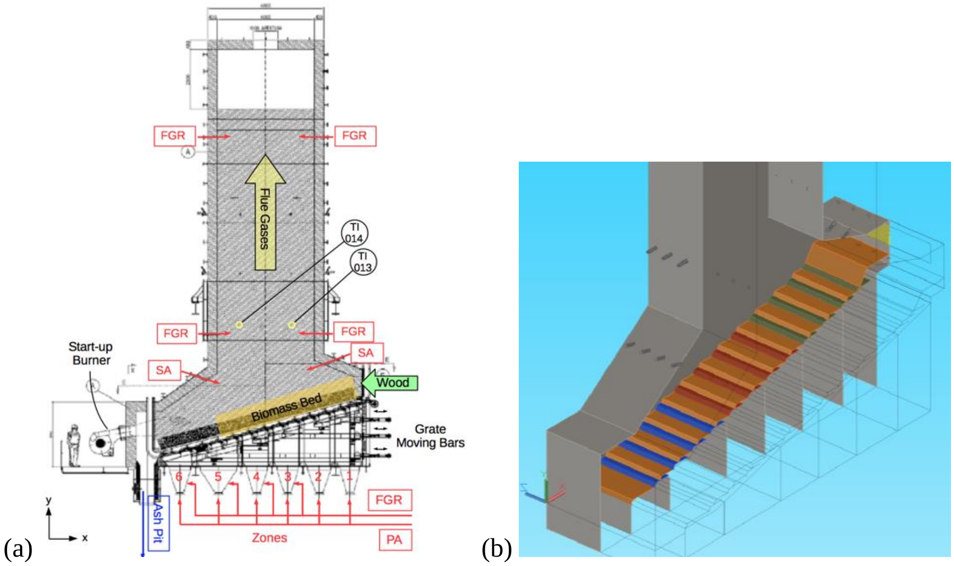

Figure 2. Sketch of the combustion chamber (a) and reciprocating grate (b).

Numerical model

In the *single-phase* approach (see Figure 3), a CFD model for the steady 3D turbulent reactive flow in the freeboard was developed with Fluent v.17 by ANSYS. The computational domain consisted of half combustion chamber. A polyhedral grid with 200k elements, refined near the small SA nozzles, was chosen. The Reynolds stress tensor was determined through the Boussinesq hypothesis and the standard k-ε model. Reaction rates were estimated by assuming fast chemistry with the Eddy Dissipation Model (EDM). Radiation was solved with the P1 model using the WSGG model to estimate spectral properties. The bed is assumed to be a diffuse and grey body with a global emissivity of 0.9. A steady-state pressure-based solver with second-order upwind interpolation and PISO algorithm for pressure-velocity coupling was employed. Convergence was checked by: monitoring the steadiness of temperature and concentrations at some specific locations in the chamber, ensuring the normalized residuals to drop below 10^{-5} and checking the overall mass and thermal balances.

The biomass bed model consists of 6 interconnected perfectly stirred reactors in which biomass undergoes evaporation, pyrolysis and char oxidation.

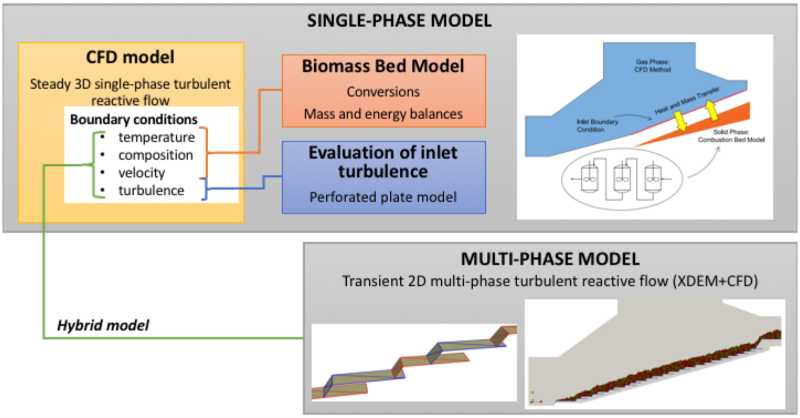

Figure 3. Conceptual scheme of the modeling methodology.

Material and energy balances are solved for each reactor by prescribing conversion values (adapted from [1], see Figure 4a) of the above processes. Volatiles are treated as a lumped species. The energy balances require a radiation flux that is recovered from the CFD model through an iterative procedure. Boundary conditions for turbulence were estimated by assimilating the flow exiting from the bed to the flow downstream of a perforated plate, whose equivalent hydraulic diameter was computed from the bed porosity $\alpha=0.8$ and mean biomass diameter $d_p = 40$ mm.

In the *multi-phase approach,* XDEM [4] [5] was employed to describe the behaviour of the two kinds of biomass particles. The model is coupled with the CFD code OpenFOAM®-Extend, that solves mass, momentum, species transport end energy equations in the gaseous phase. Hence, the CFD solution provides boundary conditions to the particles within the XDEM treatment whereas particles constitute sources/sinks of mass, momentum, chemical species and energy in the gas phase CFD equations. Due to the high computational cost required to track the particles, such kind of simulation was 2D. A piece-wise sinusoidal motion was imposed to the moving steps of the grid. As the interest of the present work was to predict the behaviour of the whole chamber including SA injection, the XDEM simulation was used to determine inlet boundary conditions for the 3D CFD model of the freeboard (*hybrid model*). The overall procedure is schematized in Figure 3.

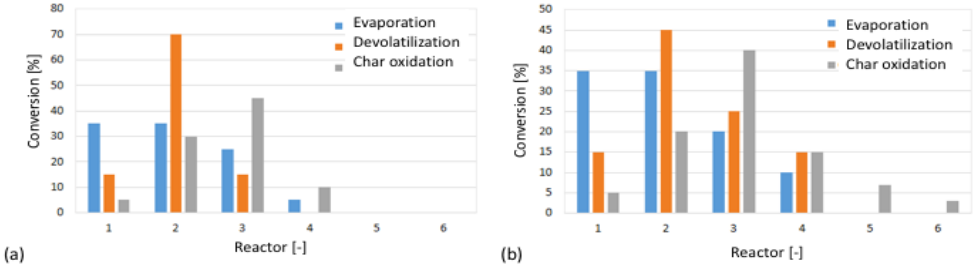

Figure 4. (a) Original and (b) revised conversions in the biomass bed reactors.

Results

The original single-phase model (Figure 5a) shows that the high temperature region is located above the bed; this is due to the high turbulent mixing, that comes from the perforated plate assumption to evaluate the inlet turbulence. The comparison between experimental and calculated temperatures (Figure 6) highlights an under-prediction of the T14 temperature, that suggested the revision of conversion values in the reactors (Figure 4b). This leads to a small improvement. Varying the turbulence levels of the flow coming from to the bed or changing the EDM constants did not lead to better matching either.

XDEM could be very appealing to remove the uncertainty related to the above conversion values inlet turbulence levels. Both thermal and CH_4 fields (Figure 7) emphasize the unsteady behavior of grate combustion, showing the presence of gas streaks coming out from the bed. In order to have a fully 3D analysis, profiles of temperature, velocity, turbulence and species were extracted above the bed and set to the 3D CFD model, resulting in the thermal field of Figure 5c. The high temperature region is shifted towards higher axial coordinates with respect to single-phase models, because the lower turbulent mixing predicted above the bed.

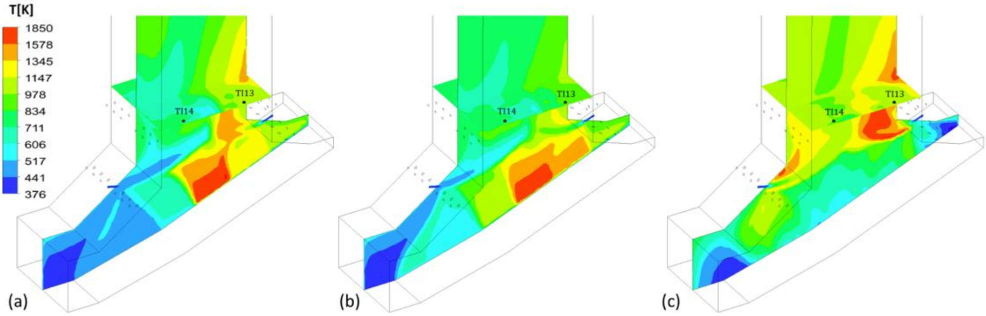

Figure 5. Distribution of temperature (K) in the vertical mid-plane and horizontal plane including the measuring locations predicted with: (a) original single-phase model; (b) revised single-phase model; (c) hybrid model.

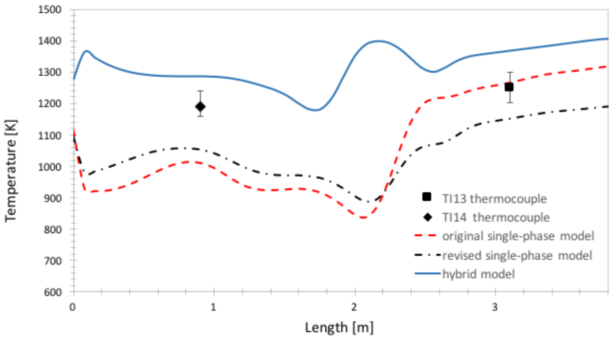

Figure 6. Predicted and experimental temperatures (K).

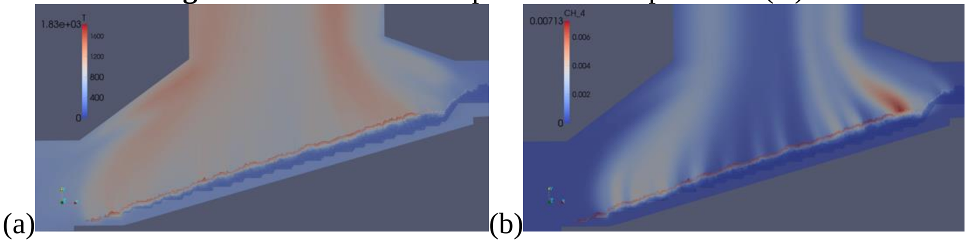

Figure 7. Instantaneous temperature (K) and methane mass fraction predicted with XDEM (2D model).

The preliminary comparison with experimental temperature measurements (Figure 6) indicated encouraging results of such hybrid model even though it over-predicts both temperature measurements.

Conclusions

Single-phase and multi-phase approaches were employed to model biomass combustion on a large-scale reciprocating grate. The single-phase approach evidenced the large uncertainties associated to the biomass bed treatment, the latter requiring knowledge of biomass conversion along the grate. Instead, multi-phase models do not require any hypothesis on conversion and may be used to determine the amount of unburnt carbon. Their large computational cost often limits the applicability to 3D analysis; hence an interesting approach proposed here is to couple the two kinds of model. The results, although preliminary, seem encouraging. Future work will attempt to improve the kinetics and the treatment of the turbulence-chemistry interaction.

References

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