EXPERIMENTAL AND NUMERICAL STUDY OF WOODCHIPS COMBUSTION IN AN UNDERFEED STOKER BOILER

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Abstract

Temperature and gas composition measurements are performed in different locations above the fire pit of a small fixed bed boiler fed with biomass woodchips. These experimental data show a large spatial variation of the values, thus suggesting that the any biomass bed model, to be eventually coupled with the freeboard numerical model, should be able to take into account such variability. Hence a numerical model of the boiler is developed by treating the biomass bed region as porous domain with sources and sinks of energy and chemical species.

Introduction

Biomass is an attractive alternative to fossil fuels for energy production because it is a widely available, renewable and CO_2-neutral energy source. Among the available technologies, small boilers are the widespread option for distributed generation; however, the design of these systems should be improved to increase the process sustainability by rising efficiency and reducing pollutant emissions. For instance, it has been shown how the process performances are affected strongly by the thermal input, air distribution and excess (e.g. [1] [2]).

Logically this goal needs a comprehensive investigation about the effect of boiler configuration and operating condition on combustion efficiency and emissions. In this scenario, computational fluid dynamics (CFD) may represent a useful design and optimization tool. However, the numerical modeling of biomass boilers is computationally very demanding and affected by many uncertainties because the presence of an unsteady multiphase turbulent combustion process. Indeed, the granular biomass phase is generally not included into the CFD simulation, which instead models just the gas phase in the combustion chamber (freeboard). The biomass bed is taken into account by means of proper boundary conditions to the CFD model, i.e. set to the interface between the biomass bed and the freeboard. Such boundary conditions may be obtained empirically or by using off-line bed models. The latter assimilate the biomass bed to a single of a series of interconnected perfectly stirred reactors (PSR), in which biomass conversion processes (drying, devolatilization and char oxidation) occur [3][4]. However. a recent work has shown how this approach is affected by high uncertainty related to the estimation of the inlet turbulence conditions which determine the turbulent mixing of volatile species and thus reaction rates [5].

In this work, temperature and chemical species are measured in different locations above the fire pit of a small fixed bed boiler fed with woodchips. Then, a numerical model is proposed by treating the biomass bed as a porous domain with sources and sinks of energy and chemical species. With this approach, the distribution of primary air can be well taken into account.

Experimental setup

The underfeed-stoker boiler has a nominal power of 140 kW and is sited at the Biomass to Energy Research Center (CRIBE) of the University of Pisa. The system was modified to fully operate with biomass, which is fed by means of a screw conveyor. Primary air is injected through 68 rectangular nozzles placed laterally with respect to the fire pit, while secondary air is fed through a manifold constituted by 7 circular pipes as shown in Figure 1a. The boiler operates slightly under pressure (20 Pa). Flue gases pass through a gas to oil heat exchanger that ultimately provides hat to CRIBE facilities [2].

The boiler was equipped with a measuring system to monitor: flue gas composition (O_2, CO, CO_2, NOx), inlet air temperature as well as the flue gas and oil temperatures upstream and downstream of the heat exchanger. The thermocouple for the flue gas upstream of the heat exchanger was equipped with a shielded cap to minimize the radiative effects [2]. Moreover, temperature and gas composition are acquired at different locations above the fire pit. The idea is to characterize the release of volatiles products. To this purpose, 6 thermocouples were placed above the biomass bed in the positions indicated in Figure 1b, i.e., 3 on the central line (L) and 3 on the lateral side (H). In addition, a movable steel suction probe allows sampling the gas above the bed. Particularly, the probe is L-shaped, and can both slide and rotate to reach all desired locations as depicted in Figure 1. The sampled gases are analyzed by means of a micro-gas chromatograph and a FTIR to provide CO_2, CO, H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2 [2].

The experimental campaigns were performed by using different thermal inputs, air excesses, secondary to primary air flow ratios, i.e. λ, as well as types of biomass, in order to investigate the effect of operating conditions on the boiler performance. In this work, the test with poplar woodchips with average diameter d_p =13 mm is considered. The biomass ultimate and proximate analyses are reported in Table 1. The total and primary air flow rates were 0.10 and 0.065 kg/s respectively (λ = 0.6), whereas the biomass flow rate was estimated to be approximately 0.033 kg/s.

Table 1. Ultimate and proximate analysis of poplar woodchips.

C	H	O	N	Moisture	VM	FC	Ash	LHV
[% daf]	[% daf]	[% daf]	[% daf]	[%]	[% dry]	[% dry]	[% dry]	[MJ/kg]
49.84	6.06	43.63	0.47	9.84	84.89	13.33	1.78	18.41

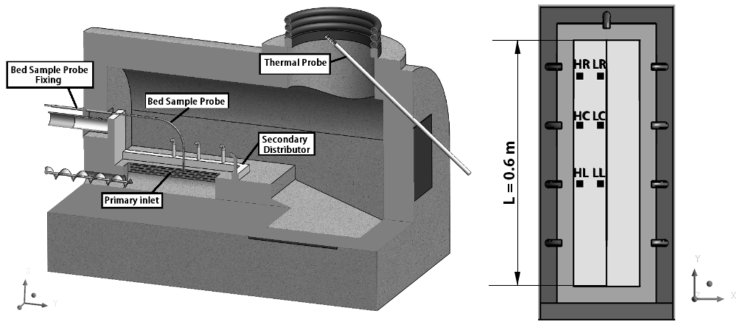


Figure 1. Scheme of (a) boiler and (b) fire pit with sampling locations.

Numerical Model

The numerical model considers a single-phase turbulent reactive flow in two different domains: a fluid domain for the freeboard and a porous domain for the biomass bed. Both domains are discretized through fully structured grid (800k and 10k cells, respectively). The freeboard grid was refined near the nozzles and generated by O-grid (Figure 2). Steady state RANS equations were solved with ANSYS Fluent 17 by means of a pressure-based solver, second upwind interpolation and SIMPLE algorithm for pressure-velocity coupling [6].

Two approaches were used to estimate the volatiles evolution in the freeboard. In approach #1, volatiles were treated as a pseudo-component, whose formula was derived from the biomass proximate and ultimate analysis. In this case the volatile oxidation was considered with a two-step global reaction scheme, assuming infinitely fast chemistry through the Eddy Dissipation Model.

$$C_{1.02}H_{2.04}O_{0.96}N_{0.00113} + 0.53\ O_2 \rightarrow 1.02\ CO + 1.02\ H_2O + 0.0056\ N_2 \qquad (1)$$

$$CO + 0.5\ O_2 \rightarrow CO_2 \qquad (2)$$

The approach #2, instead, follows the work of Neves et al. [7] and characterizes the devolatilization products by means of seven volatile species (tar, H_2, H_2O, CO, CO_2, CH_4 and other light hydrocarbons) and dry ash-free char. The composition is estimated through semi-empirical correlations [7]. In this case, the turbulence-chemistry interaction is handled with the Eddy Dissipation Concept (EDC). Due to the large computational efforts, the DRM19 reduced mechanism was used instead of a detailed one; to do this, tar was represented as CH_2O.

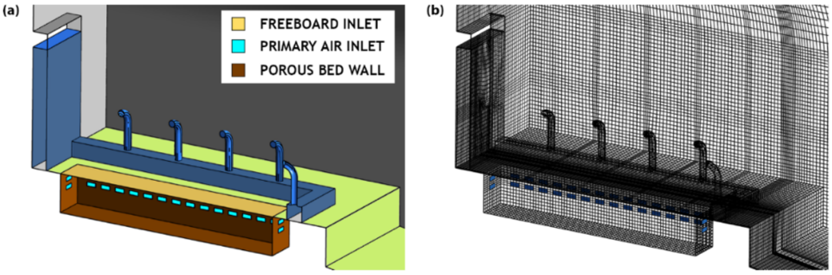


Figure 2: Detailed of porous bed with primary air inlet (a) and grid (b).

Reynolds stresses were determined by means of the k-ε model, while the radiative heat transfer equation was solved with the P1 model and WSGG method use.

The biomass bed is modeled as a porous media, thus estimating pressure drops by means of the Ergun equation:

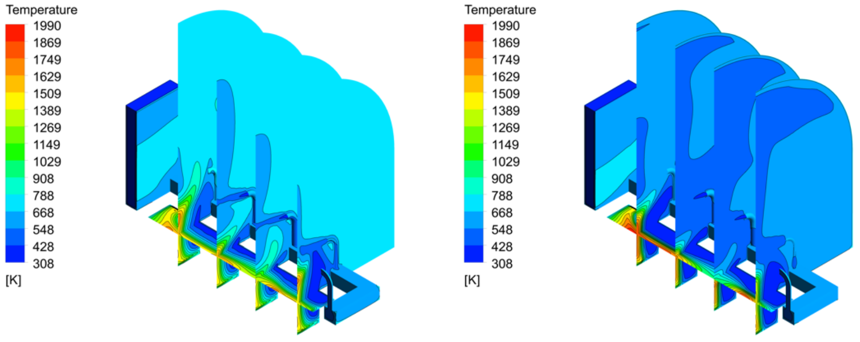
$$\frac{|\Delta P|}{l} = \frac{1}{\alpha}u_{\infty} + \frac{1}{2}\rho C_2 {u_{\infty}}^2 \tag{3}$$

with $\alpha = \frac{{d_p}^2}{150}\frac{\epsilon^3}{(1-\epsilon)^2}$ and $C_2 = \frac{3.5}{d_p}\frac{(1-\epsilon)}{\epsilon^3}$, where ϵ is the void fraction ($\epsilon = 0.5$) and d_p is the average particle diameter.

Volumetric sources and sinks of energy and chemical species were then assigned to the porous domain though a User Define Function, in order to account for drying, devolatilization and char oxidation. Such sources/sinks were estimated from energy and mass balances; basically, there are positive sources of volatiles, H_2O, CO, CO_2 and energy, and a negative source (sink) for O_2, that is consumed during char oxidation. The energy balance takes into account the radiative heat transfer with the freeboard and the boiler walls; such transfer was determined through an iterative procedure [6]. The sources/sinks were assigned non-uniformly along the porous volume because it was observed that the screw conveyor is unable to push the biomass up to the opposite edge of the fire pit. Hence full sources/sinks were set until 85% of fire pit length, while they linearly go to zero in the remaining distance.

Results

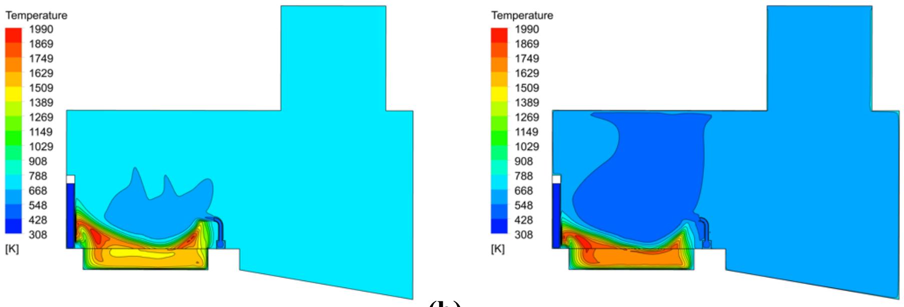
The distribution of temperature in different longitudinal sections of the boiler and in the longitudinal mid-plane are shown in Figure 3 and Figure 4, respectively, as predicted with #1 and #2 approaches. The former well matches the outlet experimental temperature, which is 687 K, whereas the predicted one (independently on the void fraction) is 693 K. The agreement concerning major chemical species is also good, e.g. measured and predicted O_2 mass fractions in the flue gas are 0.18 and 0.20, respectively. This is satisfactory, especially considering the many uncertainties (e.g. biomass flow rate) which affect the model.



(a) (b)

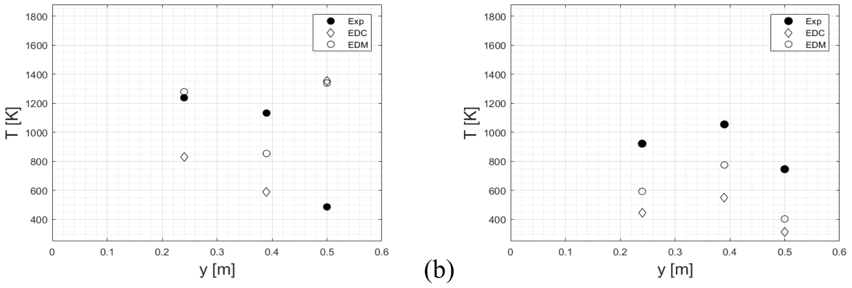
Figure 3: Distribution of temperature in transversal cross section of the boiler predicted for (a) approach #1 and (b) approach #2.

The effect of secondary air injection on the resulting flame above the bed is well evident. The secondary air, on one hand, increases turbulent mixing and hence improves reactions; however, on the other hand, it carries a cold flow. As a result, the temperature distribution along the longitudinal boiler mid-plane (Figure 4) shows the presence of a cold zone above the fuel bed, approximately at the center, while high temperature zones are pushed toward the fuel bed edges. Approach #2 shows lower temperatures, probably due to the strong assumption in the representation of tar. The comparison between experimental and predicted temperature measurements above the fire pit for different locations is provided in Figure 5 for the two models. The first two temperature near the center (Figure 5a) are reasonably predicted by approach #1, whereas the last temperature is strongly overestimated by both models; as mentioned above this may be partly imputed to fact that the screw conveyor was unable to well distribute the biomass up to the opposite edge of the fire pit. Lateral temperatures (Figure 5b) indicate an underestimation of measurements, suggesting probably an erroneous estimation of the porous domain parameters. As for chemical species, the matching between experiments and predictions should be improved. The comparison between measured and predicted CO_2 is provided in Figure 7 and indicates a large underestimation with both approaches in positions near the center.



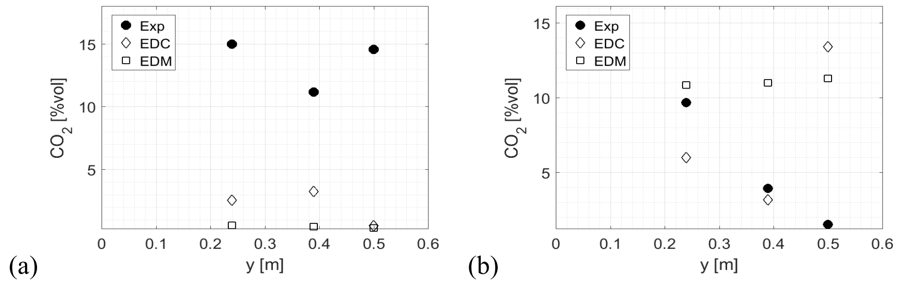
(a) **(b)**

Figure 4: Distribution of temperature in the boiler longitudinal mid-plane predicted for (a) approach #1 and (b) approach #2.



(a) (b)

Figure 6: Comparison between experimental and predicted temperatures: (a) HL, HC, HR (b) LL, LC, LR.



(a) (b)

Figure 7: Comparison between experimental and predicted CO_2 molar fractions: (a) HL, HC, HR (b) LL, LC, LR.

Conclusion

A large variation of temperature and chemical species was measured just above the fire pit of a small fixed bed boiler fed with woodchips. This suggests that biomass bed models based on a single or a series of PSR are either inadequate or difficult to be set. Instead, representing the biomass bed with a porous region with source/sinks of energy and chemical species may involve reasonable computational resources still taking into account the flow distribution induced by the primary air. A preliminary reduced kinetic model was implemented, however further efforts are needed to better represent volatiles species and incorporate proper oxidation schemes.

References

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