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Experimental and Numerical Investigation of a Small-Scale Fixed-Bed Biomass Boiler

Stefania Patronelli[a], Gianluca Caposciutti[b], Federica Barontini[a], Chiara Galletti*[a], Marco Antonelli[b], Umberto Desideri[b], Leonardo Tognotti[a]

[a]Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy.
[b]Dipartimento di Ingegneria dell'Energia, dei Sistemi, del Territorio e delle Costruzioni, Università di Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy.
chiara.galletti@unipi.it

Experimental campaigns were carried out on a 140kW fixed-bed biomass boiler to investigate the effect of primary and secondary air distribution on temperature and combustion products and to validate a numerical model. Specifically, a Computational Fluid Dynamics model for the freeboard, based on a single-phase turbulent reactive flow model, was coupled to an off-line biomass bed model that encompass evaporation, devolatilization and char oxidation of the biomass, using an iterative procedure to take into account the radiative transfer between the biomass bed and the freeboard. The inlet turbulence level affects strongly the turbulent mixing of volatiles and it was proposed to assimilate the flow from the biomass bed as that coming from a perforated plate.

1. Introduction

The use of low-grade fuels such as various biomasses is increasing rapidly because they are inexpensive energy sources with a low greenhouse gas footprint. However, their utilization calls for a number of technological challenges due to the larger feedstock variability, the higher moisture and lower heating value than coal. Fixed-bed biomass boilers are widespread options for small-scale systems; however operating conditions have been shown to significantly affect the boiler performance in terms of combustion efficiency and emissions.

Technological advancements could benefit of Computational Fluid Dynamics (CFD) tools due to their ability to solve a large number of equations in complex geometries. The application of CFD to biomass bed boilers requires appropriate description of the relevant homogeneous and heterogeneous reactions, the turbulent flow, the mass and heat transfer processes (including radiation) and their interactions. The complexity of these models is limited by the computational time, so validation of the CFD model with experimental data is still important.

Even though recently some investigations on small-scale fixed bed biomass boilers can be found (see for instance Buchmayr et al., 2015, and Serrano et al., 2013), there is still lack of experimental data as highlighted by Khodaei et al. (2015), especially in the perspective of validating CFD models.

The present work describes a joint experimental and CFD modeling activity aimed at investigating biomass combustion in a 140 kW fixed-bed boiler that generates steam for other utilities at the CRIBE ("Centro Interuniversitario di Ricerca sulle Biomasse da Energia") research area in Pisa.

2. Fixed bed boiler

The system is constituted by a 140 kW fixed-bed combustion chamber, a flue gas to oil heat exchanger and the flue gas cleaning system (see Figure 1a). The biomass is fed to the combustion chamber through a cochlea. Primary air is fed from underneath the biomass bed, whereas the secondary air is supplied through 9 injection pipes bended at the upper edge (see Figure 1c). The air flow rate is measured through two hot wire flow meters (see F in Figure 2) whereas temperatures are acquired by mean of K,J and T thermocouples (T).

A shielded probe was built on purpose to acquire the flue gas temperature upstream of the heat exchanger (see white line on the top right of Figure 1b). Concentration of chemical species in the flue gases (CO_2, CO, O_2, total hydrocarbons and NO_x) was acquired by means of an Environnement S.A. station, equipped with infrared, paramagnetic, flame ionization, and chemiluminescence detectors. All the other measurements were acquired through a National Instrument/Arduino board. A 20 Pa of depression inside the combustion chamber was maintained through a secondary fan, placed at the flue gas outlet and controlled by a pressure sensor. The air flow was regulated through an inverter, controlling the blower rotational speed, whereas the primary and secondary rates were regulated by mean of two sphere valves. Details about the control and measuring system (see Figure 2) can be found in Antonelli et al. (2016).
The temperature upstream of the heat exchanger and the flue gas composition were acquired with a 0.2 Hz sampling time, for different inlet conditions. The sampling time was 20 min in order to get steady data.

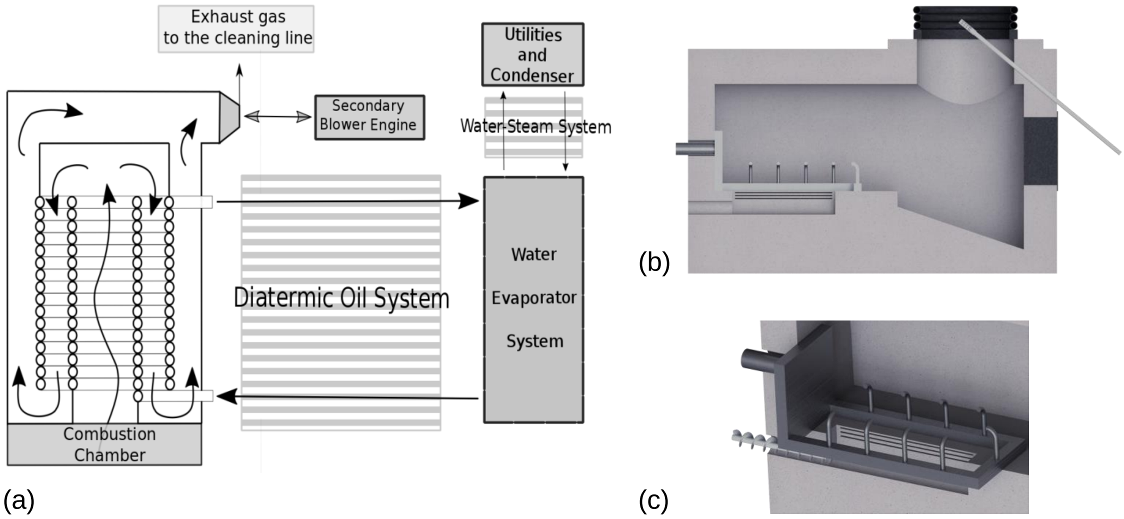


Figure 1: Scheme of the (a) combustion system, (b) chamber and (c) secondary air injection.

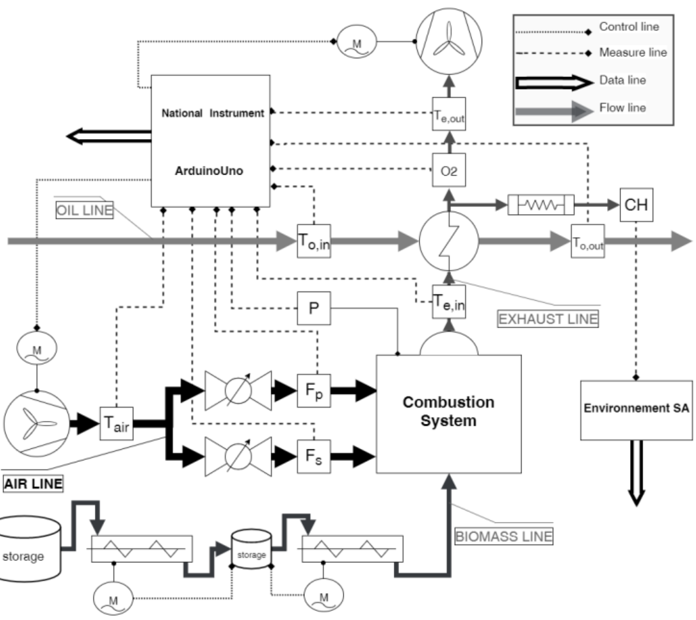


Figure 2: Control and measuring system.

The experimental tests considered here were carried out using Pine-Beech woodchips, whose ultimate and proximate analysis are reported in Table 1. The biomass flow rate was 31.2 kg/hr, whereas the air flow rate was constant and equal to 612 kg/hr for all runs. Three different secondary to primary air ratios, i.e. λ=0, $\boldsymbol{\lambda}$=0.43 and $\boldsymbol{\lambda}$=0.89, were used in the experimental campaigns.

Table 1: Ultimate and proximate analysis of Pine-Beech woodchips

C	H	O	N	S	Moisture	VM	FC	Ash	LHV
[% daf]	[% daf]	[% daf]	[% daf]	[% daf]	[%]	[% dry]	[% dry]	[% dry]	[MJ/kg]
49.20	5.73	44.86	0.21	0.00	10.6	78.72	20.38	0.90	17.88

3. Numerical model

The numerical model is based on a CFD model for the freeboard (i.e. single-phase turbulent reactive flow model) that is coupled to an off-line biomass bed model.
Specifically, the biomass bed is treated as a perfectly stirred reactor in which biomass undergoes evaporation, devolatilization and char oxidation. Hence, the reactor is fed with primary air and biomass, whose flow rate is determined from the cochlea revolution number per minute. An equilibrium calculation is performed to provide reaction products and temperatures.
Even though in literature zonal models of the biomass bed have been suggested for large scale boilers (Yin et al., 2008; Galletti et al., 2016; Hajek and Jurena, 2012), the assumption of a single reactor is justified here by the small dimensions of the biomass bed. Released products and evaluated temperature constitute inlet conditions to the freeboard CFD model. The procedure is iterative to take into account of the radiative transfer between the biomass bed and the freeboard (Hajek and Jurena, 2013).
The CFD model for the freeboard was developed with the commercial code Fluent v. 17 by Ansys Inc. The computational domain included the secondary air injection system and extended from the biomass bed to the lower edge of the heat exchanger that hence was excluded from the calculation. Thanks to the symmetry, half boiler could be considered (see Figure 3a showing also surfaces for the boundary conditions). The grid was generated with the software ICEM. Based on a preliminary grid independency study, performed using 4 unstructured grids (with number of elements ranging from 1000k to 2300k) and 4 structured grids (with number of elements ranging from 600k to 1200k), a structured grid with 800k cells was chosen (Figure 3b). The grid was generated with the multi-block approach. The circular nozzles for the secondary air injection were meshed through O-grid strategy.

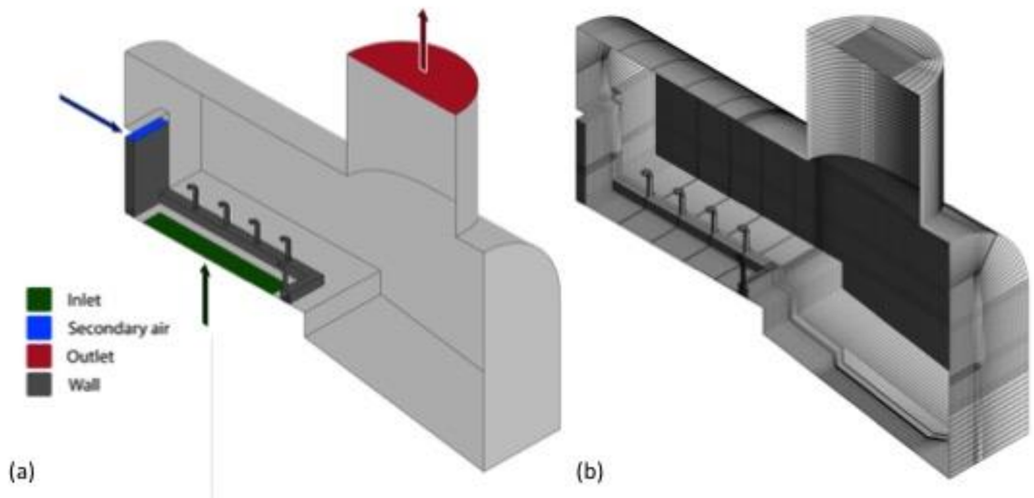


Figure 3: Computational domain (a) and grid (b).

The physical model is based on Favre-averaged equations for a single-phase reactive turbulent flow. The standard *k-ε* turbulence model was used to solve Reynolds stresses . The radiative transfer equation was evaluated through the P1 model with spectral properties estimated with the Weighted Sum of Gray Gas model. An emissivity of 0.94 was set to the chamber refractory walls, whereas a value of 0.8 was set to the secondary air injection system, made of steel.

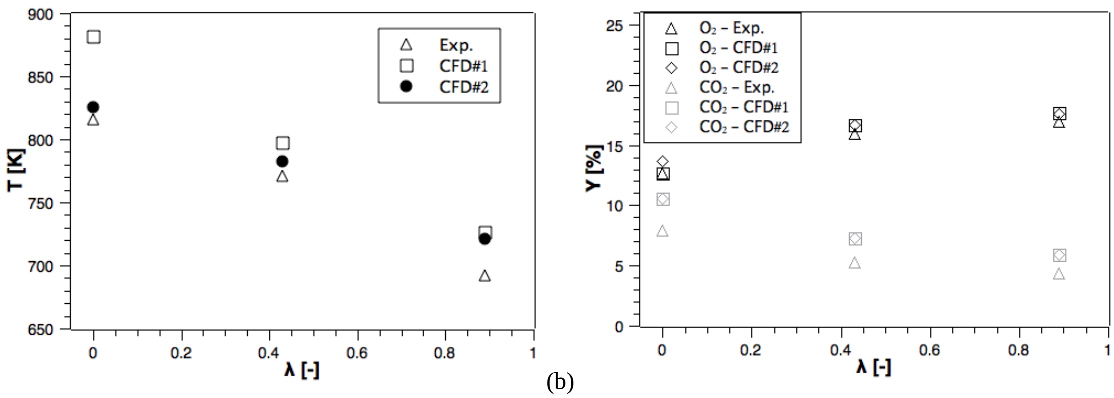
Volatiles were treated as a lumped species whose formula was derived from the biomass proximate and ultimate analysis. The Eddy Dissipation Model based on a fast chemistry assumption is used to model volatiles oxidation, described with a 2-step reaction scheme as:

$$C_{0.9}H_{2.14}O_{1.05}N_{0.0057}+0.45O_2 \rightarrow 0.90CO+1.07H_2O+0.0028N_2$$
$$CO+0.5O_2 \rightarrow CO_2 \quad (1)$$

A pressure-based solver with a Second Order Upwind discretization and SIMPLE algorithm for the pressure-velocity coupling was employed.
The flow from the biomass bed is taken to be normal to the inlet surface. The boundary conditions for the *k* and *ε* equations were obtained according to two different assumptions:
- CFD model #1 - fully developed flow from a pipe of diameter equal to the equivalent diameter of the inlet section (i.e., d_e=0.25 m) and a turbulence intensity of 5%;
- CFD model #2 - flow from a perforated plate, with scale length equal to the hole hydraulic diameter (i.e., l_s = 0.008 m, estimated from the biomass mean diameter d_m =10 mm and void fraction α =0.5) and turbulence intensity of 35% (Hall and Hiatt, 1996). A preliminary CFD model treating the biomass region as a porous media of particles of diameter d_m =11 mm, indicated that such value for the turbulence intensity is reasonable.

4. Results

Figure 4a compares temperatures measured upstream of the heat exchanger with those predicted by the CFD model for different secondary to primary air flow ratios *λ*. Even though the trend is captured, there is an overprediction of temperature, that is particularly evident for CFD model #1 and ratio *λ*=0 (i.e., no secondary air). Similarly, Figure 4b compares experimental and predicted mass fractions of CO_2 and O_2. The agreement is very good especially for the latter species, whereas an overestimation of CO_2 mass fraction by of 2-3% is observed, that can be imputed to some uncertainties on the boundary conditions and especially on the biomass flow rate.
The distributions of temperature on the boiler longitudinal mid-plane obtained for different secondary to primary flow rate ratios are reported in Figure 5 and Figure 6 for CFD model #1 and #2, respectively. It can be observed that the inlet turbulence conditions strongly affect the resulting thermal field. In absence of secondary air, CFD model #1, characterised by low turbulence levels, predicts that the high temperature region is located close to the top wall of the combustion chamber (see Figure 5b). This is because the turbulent mixing is so low in the bulk of the chamber, that reactants do not mix and thus volatiles oxidation does not take place near the bed. Instead, CFD model #2 (see Figure 6b), that assimilates the flow coming from the biomass bed to the flow coming from a perforated plate, characterised by higher turbulence levels, predicts a significant turbulent mixing above the bed that leads to volatiles oxidation and hence to high temperatures, more in agreement with experimental observations.
The temperature distribution at different cross sections in the chamber are shown in Figure 7 as obtained with the CFD model #2. It can be noticed the strong three dimensional flow generated from the secondary air injection nozzles. With increasing the secondary to primary flow ratio, the reaction region moves closer to the biomass bed due to the strong mixing generated by the secondary air flow. In case of low primary air (i.e. *λ*=0.89) the presence of high temperature regions can be observed whereas the temperature is more uniform for smaller secondary to primary flow ratio (*λ*=0.43).



(a) (b)

Figure 4: Comparison between experimental measurements of (a) temperature, (b) O_2 and CO_2 mass fractions and those predicted with the CFD model #1 and #2 for different secondary to primary air flow ratios.

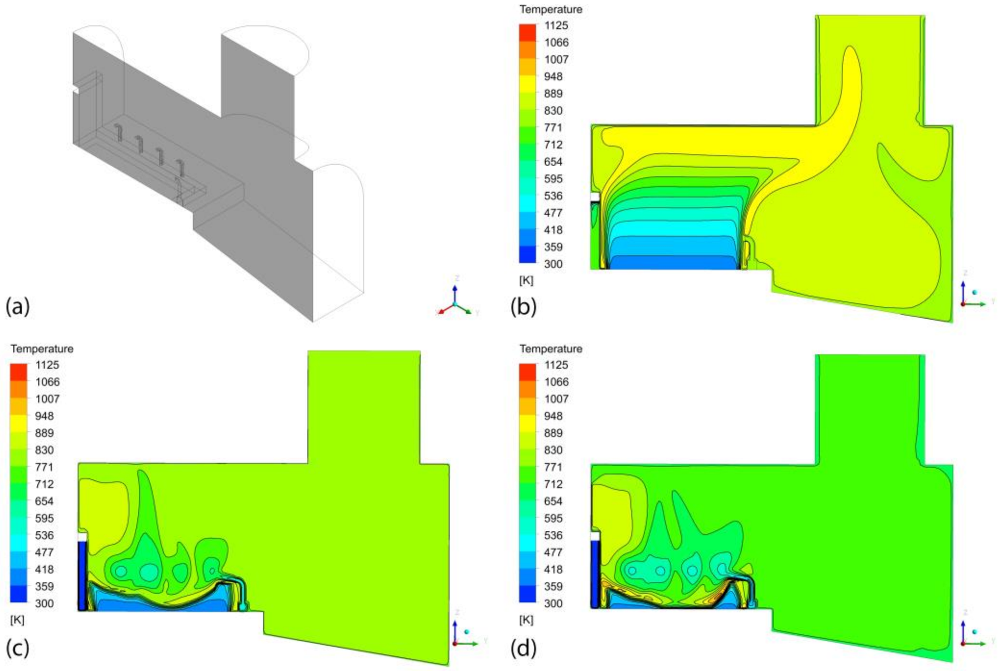


Figure 5: Distribution of temperature on the boiler symmetry (a) predicted with CFD model #1 at different secondary to primary air flow ratios: (b) λ=0, (c) λ=0.43, (d) λ=0.89.

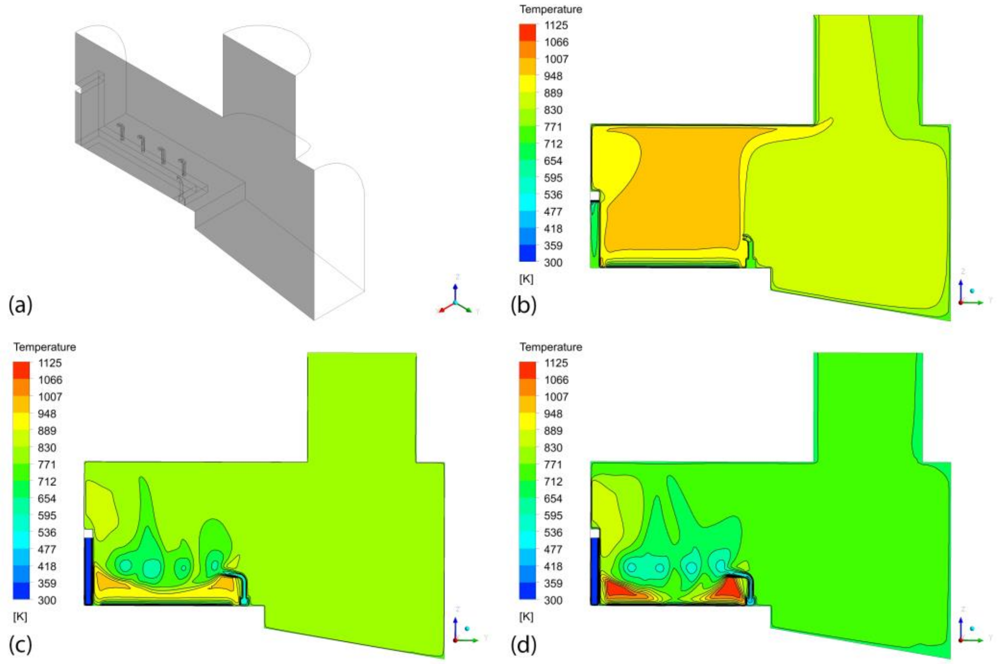


Figure 6: Distribution of temperature on the boiler symmetry (a) predicted with CFD model #2 at different secondary to primary air flow ratios: (b) λ=0, (c) λ=0.43, (d) λ=0.89.

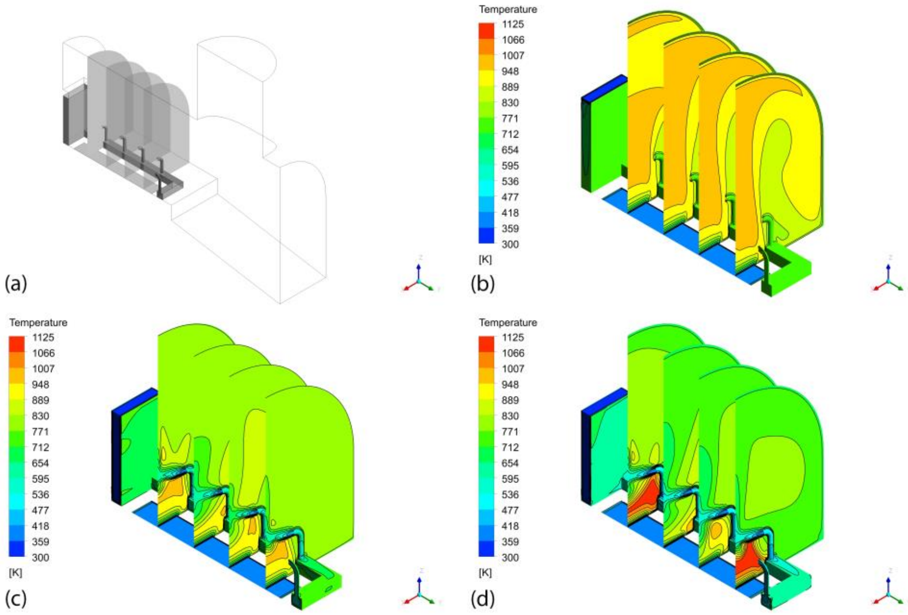


Figure 7: Distribution of temperature at different cross sections in the boiler (a) predicted with CFD model #2 at different secondary to primary air flow ratio: (b) λ=0, (c) λ=0.43, (d) λ=0.89.

5. Conclusions

A small-scale fixed-bed biomass boiler has been equipped with control and measuring systems to carry out experimental campaigns in order to investigate the effect of primary and secondary air distribution on temperature and combustion products. A numerical model of the boiler, based on zero-dimensional reactor model of the biomass bed and a CFD model for the freeboard, was found to be able to predict the outlet temperature and major species with satisfactory accuracy. The model is very sensitive to the inlet turbulence conditions that affect the turbulent mixing of volatiles with air and hence reaction rates. The evaluation of turbulence levels from the biomass bed as those from a perforated plate leads to a thermal field that is consistent with experimental observations. The measuring system will be upgraded in the next future to allow in-flame measurements of chemical species with a FTIR spectrometer and thus a better validation of the model. The latter will be also improved to better consider the effect of turbulence and kinetic modelling.

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