Fuel 221 (2018) 128–137

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Combustion of wood-chips in a small-scale fixed-bed boiler: Validation of the numerical model through in-flame measurements

Stefania Patronelli[a], Marco Antonelli[b], Leonardo Tognotti[a], Chiara Galletti[a,*]

[a] Department of Civil and Industrial Engineering, University of Pisa, Italy
[b] Department of Energy Engineering, Systems, Land and Buildings, University of Pisa, Italy

ARTICLE INFO

Keywords:
Biomass
Porous model
Computational Fluid Dynamics
Under-feed stoker

ABSTRACT

Experimental campaigns and numerical simulations were carried out to investigate the effect of air distribution on the performance of a small-scale fixed-bed boiler fed with biomass. Despite the small dimension of the fire pit, temperature measurements just above it showed a large spatial variation, thus indicating that modeling approaches based on perfectly stirred reactor conditions for the biomass bed are not suited. Moreover these approaches, often used for small boilers, suffer of high uncertainty related to the inlet turbulence levels that affect the mixing of reactants and thus reaction rates. Instead the representation of the biomass bed as a porous medium with defined sources and sinks of chemical species and energy, may provide a cheap and effective strategy to take into account the distribution of the primary air and overcome uncertainties on inlet turbulence. Results are encouraging with a good prediction of the trends of the available measurements. Significant discrepancies were noticed in some locations, hence calling for further efforts to improve the description of the kinetics as well as of the biomass dimensional distribution needed for the definition of the porous medium.

1. Introduction

The use of biomass as renewable energy source is becoming more and more attractive due to the concern about global warming related to greenhouse gas emissions [1] as well as the limited availability of fossil fuel sources [2]. Biomass combustion is one of the main paths to bioenergy, even though it calls for a number of issues related to energy efficiency and pollutant emissions.

Among the available technologies, small-scale boilers are appealing for distributed energy generation as for residential or mini-district heating as well as for carrying out fundamental research [3,4].

The main operating variables controlling fixed-bed boiler efficiency and pollutant emissions are the thermal input, air excess and distribution. In particular, the secondary to primary air split ratio λ is an important variable affecting the system performance [5]. For instance Wiinikka and Gebart [6] investigated experimentally how different air supply strategies influence particulate matter emission from fixed-bed combustion of biomass. Pettersson et al. [7] analyzed the effect of design changes controlling temperature and/or residence time, on the emission performance and characteristics of a laboratory fixed-bed reactor fed with pellet. Recently Khodaei et al. [8] compared experimentally two different configurations for the secondary air distribution in a 15 kW fixed-bed under-feed combustor, showing their large impact on the temperature in the post-combustion zone, as well as on CO and particulate matter emissions.

All the above works agree on the fact that there is large room of action to improve the available technologies in terms of efficiency and pollutant emissions. This would require comprehensive investigation on the effect of combustion chamber and inlet design, as well as on the operating conditions, including the biomass characteristics.

In this framework, Computational Fluid Dynamics (CFD) tools, that allow solving several transport equations describing the relevant phenomena in complex geometries, may add significant contribution to the system optimization, providing a description of the thermo-chemical field in the whole combustion chamber. However, the application of CFD to biomass-fired boilers is challenging because it requires an appropriate description of the relevant homogeneous and heterogeneous reactions, the turbulent flow, the mass and heat transfer processes (including radiation) and their interactions.

Fully multi-phase models have been proposed recently. Among them, Lagrangian–Eulerian model have received some attention because their ability to well deal with phenomena acting at the particle size. In particular, the granular biomass phase can be solved with a discrete element method (DEM) opportunely coupled with CFD for the gaseous phase. Examples of this modeling strategy are provided by Peters and co-authors [9,10]. However, it is clear how a high level of

---

[*] Corresponding author.
E-mail address: chiara.galletti@unipi.it (C. Galletti).

https://doi.org/10.1016/j.fuel.2018.02.083
Received 5 December 2017; Received in revised form 8 February 2018; Accepted 10 February 2018

Nomenclature

Symbols

A,B	constants of the EDM combustion model [–]
C_2	inertial coefficient [m^{-1}]
C_μ,$C_{\varepsilon1}$,$C_{\varepsilon2}$	constants of k–ε turbulence model [–]
c_p	specific heat [$J\ kg^{-1}\ K^{-1}$]
D	diffusivity [$m^2\ s^{-1}$]
d_p	particle diameter [m]
D_h	hydraulic diameter [m]
h	enthalpy [$J\ mol^{-1}$]
ΔH_{dev}	heat of devolatilisation [$J\ kg^{-1}$]
I	identity matrix [–]
$\dot{m}$	mass flow rate [$kg\ s^{-1}$]
k	turbulent kinetic energy [$m^2\ s^{-2}$]
ℓ	turbulent length scale [m]
LHV	lower heating value [$J\ kg^{-1}$]
M	mass fraction of moisture in biomass [–]
p	pressure [Pa]
Pr_t	turbulent Prandtl number [–]
Q	heat [J]
S_i	source term in the momentum equation in the i-th direction [$kg\ m^{-2}\ s^{-1}$]
Sc_t	turbulent Schmidt number [–]
T	temperature [K]
TI	turbulent intensity [–]
$\mathbf{u}$	velocity vector [$m\ s^{-1}$]
V	volume [m^3]
W	molecular weight [$kg\ mol^{-1}$]
X	mass fraction in biomass [–]
Y	mass fraction in gas phase [–]

Greek symbols

α	thermal conductivity [$m^2\ s^{-1}$]
α_p	permeability of the porous bed [m^{-2}]
ϵ	void fraction [–]
ε	turbulent dissipation rate [$m^2\ s^{-3}$]
λ	secondary to primary air flow ratio [–]
μ	viscosity [$kg\ m^{-1}\ s^{-1}$]
ν'	stoichiometric coefficients [–]
ω	source or sink of a chemical species due to reaction [$mol\ m^{-3}\ s^{-1}$]
ρ	density [$kg\ m^{-3}$]
σ_k,σ_ε	turbulent Prandtl numbers for k and ε [–]
$\widetilde{\varphi}$	Favre-average of the φ variable

Subscripts/superscripts

a	air
avg	average
b	biomass
dev	devolatilization
ev	evaporation
exc	excess
f	flue gas
free	in flue gases
hole	hole
inlet	related to the inlet
k	chemical species
l	liquid water
p	particle
P	products
pa	primary air
r	radiation
R	reactants
ref	reference
sa	secondary air
st	stoichiometric
T	transpose matrix
t	turbulent
tot	total
υ	steam
vol	volatiles

Abbreviations

CFD	Computational Fluid Dynamics
DEM	Discrete Element Method
EDC	Eddy Dissipation Concept
ED/FR	Eddy Dissipation/Finite Rate
EDM	Eddy Dissipation Model
PSR	Perfectly Stirred Reactor

modeling detail involves too high computational times and resources, often not balanced by the many sources of uncertainties that may affect the analysis (e.g., particle size and shape, moisture content, feeding system, etc.).

For this reason, the most widely used approaches in literature for modeling biomass boilers, are based on single-phase CFD simulations of the gaseous turbulent reactive flow in the freeboard. The impact of the biomass bed is taken into account through boundary conditions (set at inlet of the freeboard CFD model, represented by the top surface of the biomass bed), that are recovered from simplified description of the solid fuel bed [11–13].

The first kind of this approach is very simple and consists in using experimental data to define such boundary conditions [14]. However this model requires experimental data above the biomass bed, that sometimes can be difficult to obtain with sufficient spatial and temporal accuracy.

The second approach consists in developing a simplified model of the biomass bed that can be used to derive the boundary conditions for the CFD freeboard model. For instance the biomass bed can be seen as one or a series of interconnected perfectly stirred reactors PSR, in which mass and energy balances are solved with prescribed conversions of all processes which biomass undergoes (evaporation, devolatilization, char oxidation). This may lead to either uniform (in case of a single reactor) or step-wise (zonal) boundary conditions (in case of a series of reactors) [15,16], consisting of temperature, chemical species flow rate and concentration. Some authors have considered this coupling to be one directional, i.e. the solution of the bed and the freeboard can be performed sequentially by neglecting the effect of the freeboard on the bed. However, some researches argued that the coupling through radiation interaction cannot be neglected and this requires the knowledge of the thermo-chemical field in the combustion chamber. Hence iterative procedures have been proposed to evaluate the radiative flux on the bed, needed to solve the energy balance on the PSR network. Logically, also this biomass bed approach requires for a knowledge or a guess of the biomass conversion along the bed. Moreover, a recent work highlighted the importance of a good estimation of the turbulence levels at the interface between the biomass bed and the freeboard [17].

Unfortunately there is still a lack of comprehensive experimental data, that can be employed for an accurate setting of the simplified models; the main difficulty is that these data should be taken above or inside the biomass bed. Moreover, there is also lack of good experimental data set that can be used for CFD modeling validation. Most of