Energy xxx (2014) 1–10

Contents lists available at ScienceDirect

Energy

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

Engineering bed models for solid fuel conversion process in grate-fired boilers

M. Costa [a], N. Massarotti [a, b], V. Indrizzi [a, e, *], B. Rajh [c, **], C. Yin [d], N. Samec [c]

[a] Istituto Motori, Consiglio Nazionale delle Ricerche, Viale Marconi 4, 80125 Napoli, Italy
[b] Dipartimento per le Tecnologie (DiT), Università di Napoli "Parthenope", Centro Direzionale, Isola C4, Napoli, Italy
[c] Faculty of Mechanical Engineering, University of Maribor, 2000 Maribor, Slovenia
[d] Department of Energy Technology, Aalborg University, 9220 Aalborg East, Denmark
[e] School of Metallurgy and Materials, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form
4 July 2014
Accepted 21 July 2014
Available online xxx

Keywords:
Biomass conversion
Bed model
Solid fuel
Grate boiler

ABSTRACT

A comparison between two numerical models describing the thermo-chemical conversion process of a solid fuel bed in a grate-fired boiler is presented. Both models consider the incoming biomass as subjected to drying, pyrolysis, gasification and combustion. In the first approach the biomass bed is treated as a 0D system, where the thermo-chemical processes are divided in two successive sections: drying and conversion. Phenomenological laws are written to characterize the syngas release as a function of the main governing parameters. The second model is an empirical 1D approach. Temperature, species concentrations and velocity of the syngas provided by the two models are compared. Sensitivity analyses with respect to the drying agent mass flow rate, the initial moisture content and the composition of the biomass are performed. The relative error between the mean values of the temperature and velocity of the syngas predicted by the two models is equal to about 7%. The application to different types of biomass shows that the difference in the predictions increases as the carbon content grows. The phenomenological model, in fact, generally considers higher conversion rates of this element to volatiles with respect to the analogy model.

1. Introduction

The worldwide concern about the limited availability of fossil fuels and global warming mainly due to CO_2 emission has spurred interest in using biomass for energy production. Biomass combustion, as an enabled technology to achieve the pressing near-term targets for significant increase of the share of renewable energy sources in energy systems and reduction in CO_2 emissions, has been successfully demonstrated in over 200 power plants globally. However, due to the great diversity in biomass resources, efforts still need to be made to refine the combustion technology in order to achieve more efficient, cleaner biomass combustion with greater fuel flexibility. For instance, biomass combustion may have more severe pollutant emissions, deposition and corrosion tendency as a result of the high content of chlorine, sulphur and heavy metals and the comparatively low ash melting temperature [1–3].

As a tool of analysis, numerical modelling, applicable to different scales, proves being very powerful. It can eliminate the need to resort to scaling-up of results deriving from lab-scale experiments. This is very significant for studying combustion processes, for which scale-up procedures are generally complicated by the strong interaction between turbulence, reaction kinetics, heat release and radiation [4].

Grate combustion is a well developed technology for burning biomass fuels with energy recovery, as well as for the thermal treatment of municipal solid waste in waste-to-energy systems [1,5–7]. In moving grate furnaces, a stack of biomass or waste is supplied on a grate and moves lengthwise along the grate. Subjected to the radiation heat transfer from the flame in the freeboard and convective heat transfer from the primary air entering from beneath the grate, the biomass in the fuel bed will be heated-up and then experience a series of conversion processes (i.e., moisture evaporation, devolatilization and pyrolysis, and solid char oxidation) along the grate length, releasing a large amount of combustibles in the freeboard. These will undergo combustion due

---

[*] Corresponding author. School of Metallurgy and Materials, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom.
[**] Corresponding author.
E-mail addresses: v.indrizzi@libero.it, vxi239@bham.ac.uk (V. Indrizzi), bostjan.rajh@gmail.com (B. Rajh).

http://dx.doi.org/10.1016/j.energy.2014.07.067
0360-5442/© 2014 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Costa M, et al., Engineering bed models for solid fuel conversion process in grate-fired boilers, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.07.067

to the supply of a secondary air stream. The fuel bed conversion and freeboard combustion are two highly interdependent processes in a grate boiler, which have to be appropriately considered in a modelling approach.

For freeboard combustion modelling, 3D (3-dimensional) CFD (computational fluid dynamics) is often performed, in which continuity, momentum, energy and species transport equations integrated with appropriate turbulence models, radiation models, combustion models and pollutant formation models are numerically solved, as reported e.g. in Refs. [8–13]. The CFD model of the freeboard combustion also needs to be coupled with a certain fuel bed conversion model: the latter provides the velocity, temperature and species profile along the grate length on the top of the fuel bed to the former as the grate inlet condition, while the former provides the incident heat fluxes to the latter.

For fuel bed conversion simulation, very different approaches exist. Following the classification of De Souza Santos [14], the problem of solid fuel bed conversion may be faced by developing phenomenological models based on the solution of fundamental equations – such as the laws of thermodynamics and laws of mass, energy, and momentum conservation and constitutive equations – or by analogy (empirical or semi-empirical) models that mimic the behavior of the fundamental aspect of the process. The phenomenological models may be further classified on the ground of the level of the assumed simplifications, starting from zero dimensional time independent schemes (0D–S or 0D steady models) based on the thermo-chemical equilibrium assumption between participating species at the gasification temperature, to reach 3D dynamic models (3D-D or 3D dynamic models) accounting for both the spatial and temporal dependence of the relevant variables. The highest level of simplification for solid bed conversion can be found in the models of refs. [15–17], while the models in Refs. [18–21] are characterized by increased complexity. A comparison between different simplified approaches can be found in the recent paper by Mendiburu et al. [22]. Analogy based analyses are proposed in Refs. [23–27].

In the present work, two simplified, engineering models for solid fuel bed conversion, which fall in the two different categories of phenomenological and analogy models, are presented and compared. The aim is to define whether the phenomenological model or the analogy model may be of help in the system optimization for different relative amount of fillers (e.g. air-to-fuel ratio), or to furnish a reliable prediction of the syngas composition and pollutants concentrations in the flue gases. The first model is a 0D-S model, mainly based on mass balance and energy conservation equations, which are solved numerically [18]. The second is a semi-empirical one-dimensional model analogous to the one presented in Refs. [26], where an experience-based conversion rate for the treated biomass is assigned as a function of the position on the grate.

The comparison between the two proposed models is made with reference to the thermal treatment of straw in an 88 MW grate-fired boiler. The actual temperature and mass flow rates of the primary air and the feeding rate and temperature of the biomass, together with an incident heat power of 1.6 MW from the freeboard onto the top of the biomass bed, are appropriately considered in both the models. The incident heat power is assumed to be uniformly distributed over the entire biomass bed. Then, some model-based sensitivity analyses are performed, by applying both the models to different biomass fuels (e.g., wood waste and refuse derived fuels) of different compositions and comparing their predictions.

2. Two-zone zero dimensional steady model

In grate boiler burners, the biomass is fed on a moving grate to form a bed of solid material subjected to thermo-chemical treatment. The biomass starts from some initial conditions and moves along the grate undergoing variations in composition, volume and mass. The numerical simulation of the fuel bed in the solid phase, therefore, must be based on assumptions able to schematize the processes as a function of the occupied position along the grate. This is why pure 0D-S models, as the one proposed in Refs. [15], are not preferable in comparison with models accounting for lengthwise subdivision of the fuel bed into two successive processes, namely drying and conversion, as illustrated in Fig. 1. Conversion includes pyrolysis, gasification and combustion.

In the present work the two-zone 0D-S model proposed by Deydier et al. [18] is applied to solid fuels of given composition. The model assumes that the system operates under steady conditions and that the working pressure is constant and equal to the atmospheric pressure ($P_0 = 101{,}325$ Pa). In addition, it is supposed that gaseous species can be described as ideal, and that the outgoing species from the conversion section are in thermo-chemical equilibrium.

In order to numerically solve the problem, an implicit method (Newton Raphson) is used. Actually, the two sections in which the grate is subdivided are solved separately, one after the other. In order to improve convergence, some limits to variables are enforced. Minimum temperature is set to 273 K, while gases mass fractions are constrained to values between 0 and 1. In the following, details are given relative to the two treatment sections.

2.1. Drying

Biomass drying is a process aimed at reducing the initial moisture content, hence at decreasing weight and volume of the initial solid fuel. It may be considered a thermal process that allows the separation between the solid and liquid phases at any temperature. Evaporation takes place due to the admission of primary air (dry air heated) from the area below the grate and to the incident heat radiation from the flame and hot walls in the freeboard. When the air heats the biomass, the liquid water evaporates and, consequently, the humidity of the air increases. Products of this process are a refusal with a lower moisture content (or dry biomass if the evaporation is complete) and moist air. The drying section is schematized as an open system, as shown in Fig. 2. From the left side, the biomass enters at a temperature T_0 with a mass flow rate (feed rate) $\dot{m}_0$, characterized by a given composition, as for the straw here given in Table 1. From the bottom, primary air enters at temperature T_1 and mass flow rate$\dot{m}_1$; it is considered as dry air (23% oxygen and 77% nitrogen in weight). On the right exit section there is totally or partially dry biomass, and, on the top, a mixture of gas (moist air) comes out. An incident heat radiation $\dot{q}_{\mathrm{ray}}$ is also assumed.

In the drying process two cases are possible: partial and complete evaporation. In order to know which one takes place, a check about the water mass fraction must be done. In particular, the necessary amount of water for complete drying and the one relevant to the saturated case are calculated in terms of mass fraction, and compared. If the necessary amount of water for complete drying is lower than the other, complete drying occurs. Hence, depending on the evaporated water mass fraction, it is possible to have:

- partial evaporation:

In reference to the Andrew's diagram, if temperatures are such as to have balance between water vapor and liquid water, there is a partial evaporation, whereby the amount of formed steam is equal to the amount of saturated vapor;

Please cite this article in press as: Costa M, et al., Engineering bed models for solid fuel conversion process in grate-fired boilers, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.07.067