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Review

An overview of processes and considerations in the modelling of fixed-bed biomass combustion

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ABSTRACT

Biomass fuel is an environmentally friendly renewable energy source and carbon-neutral (non-fossil) fuel alternative. To facilitate its wider uptake, significant efforts are undertaken to model and experimentally study biomass combustion processes, in both industrial-scale (grate fired) and small-scale (lab-scale) combustors. In many studies, the core aim is to better understand the relationship between thermal conversion processes (drying, pyrolysis, char conversion) and their interrelationship to combustor performance (efficiency, emissions, process temperatures, scale formation, and instabilities). However, due to the complexity of solid fuel (particle) conversion and fuel bed behaviour, precise modelling of all aspects of biomass fixed-bed combustion is not readily achievable.

Despite the existence of excellent experimental and modelling studies on numerous aspects related to the characteristics of forestry derived biomass fuels and their combustion, research in this field is challenging. Complications arise from the multitude of fuels used, the varying geometries and combustor configurations investigated and the different modelling methodologies adopted to resolve steady-state and transient operation.

The literature includes works on various aspects of biomass combustion, including that undertaken in fixed-beds. However, whilst these works are valuable, they do not sufficiently cover the methods and fundamentals to model direct thermal conversion, at the bed and particle-level. The aims of the present study are to provide a fundamental overview of the methodologies employed in the modelling of laboratory-scale fixed-bed combustors. The paper also includes treatment of the fundamental thermo-physical fuel characteristics which need to be considered when undertaking macro-scale (bed-level) modelling. The paper concludes with summary observations in relation to the modelling of fixed-bed combustion as well as some opportunities which warrant further research and the challenges to be overcome.

1. Introduction

There is a need to alleviate more extensive use of fossil fuels to help satisfy global energy demand. If derived sustainably, biomass is unique in that it provides the only renewable source of fixed carbon [1,2]. According to the IEA (International Energy Agency), the total global consumption of biofuels and waste has increased from 617 Mtoe[1] in 1973 to about 1311 Mtoe in 2011 [3]. Biomass energy sources include gaseous, liquefied and solid fuels which can be derived from either low temperature (biological) processes, but also utilized in high temperature (thermal conversion) in relation to agricultural and municipal waste. The use of biomass derived power has increased during the last few decades with greater overall process efficiencies obtained through CHP (Combined Heat and Power) systems. However, there remain challenges associated with applying and optimising this technology which makes biomass energy conversion seemingly too inefficient to be a commercially and environmentally viable alternative to traditional finite fuels, such as oil and natural gas. Some of the technical barriers impeding wider use of solid biomass fuels include a better understanding of the parameters affecting combustion performance in large and complex industrial plants used to derive heat and/or power.

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[1] The amount of energy released by burning one tonne of crude oil.

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The literature includes numerous treatises in which biomass combustion has been described and reviewed to different extents. A process level classification of biomass technology and its applications has been described by Bridgwater [1]. Yin et al. [4] focused on grate firing of biomass and reported on boiler deposit formation, emission mechanisms, secondary air distribution and modelling. However, some of these works do not include a comprehensive discussion of thermal conversion at the sub-process level. Combustion characteristics of various types of biomass fuels and the problems associated with using these fuels in boiler systems have also been studied by Demirbas [5,6], but modelling details were again omitted. There have also been some reviews of fixed-bed biomass combustion but whilst these articles are valuable, they do not sufficiently cover direct thermal conversion. In particular, Obaidullah et al. [7] outlined particle emissions from small-scale biomass combustion considering particle formation, measurement techniques, mass concentrations and size distributions. However, their paper focused on primary particle formation in the combustion zone. Detailed drying and pyrolysis of wood were also reviewed by Bellais [8], Zaror [9] and di Blasi [10] who included one- and multi-component mechanisms of pyrolysis reaction and secondary reactions of tar cracking, but only focused on micro-scale (single biomass particle) modelling. An overview of the modelling of small-scale fixed-bed biomass pellet boilers with accompanying results from simplified CFD (Computational Fluid Dynamic) simulations is presented by Chaney et al. [11].

Industry scale (non-fluidised) bed combustion typically incorporates moving grates that can have megawatt thermal capacity and be integrated into power generation [12]. At a smaller scale, there are also fixed-bed (incorporating stationary grates) biomass combustors in the form of lab-scale units used for research as well as household units used primarily with boilers or heaters. Counter-current fixed-bed configurations have been widely studied due to their similarity with finite (short) bed distances along the length of industrial moving grate combustors. With this in mind, there are similarities between conversion in smaller fixed-bed and much larger moving grate combustors. Due to the relatively small horizontal gradients (horizontal waste moving direction) as shown in Fig. 1. Therefore, studies of fixed-bed combustion have advanced our understanding of issues such as the bed temperature profiles [13], burning rate [13,14], thermal efficiency [15,16], gas release from the bed surface [17] and instabilities such as channelling [18]. Laboratory scale combustors are also preferred over larger scale systems because they offer well-controlled and reproducible conditions, make it easier to apply data acquisition equipment and minimise the cost of investigations based on operation and maintenance costs.

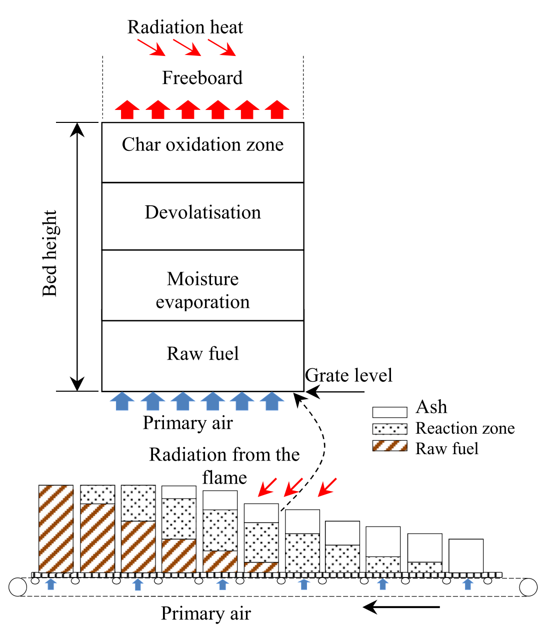

Fig. 1. Similarity between industrial moving grate (bottom) and laboratory fixed-bed combustors (top).

There are different parameters affecting the overall performance of moving grate combustors, such as primary air flowrate, streamwise velocity, secondary air staging flowrate, air distribution systems, grate size perforation distribution, particle emissions and fuel specifications. In the streamwise direction, the combustor chamber is divided into two main areas: the first zone above the grate is a packed-bed zone which is filled by a finite number of solid fuels (for example, pellets) followed by a secondary zone also known as the freeboard. The published literature largely lacks concise, but sufficiently scoped, comprehensive treaties into the governing formulations, characterization and contemporary works undertaken into solid fuel biomass combustion. The objective of this paper is to provide a detailed overview of biomass (thermal) conversion applicable to laboratory-scale fixed-beds. The main coverage of the present study is structured as follows:

Fixed-bed configurations: The geometrical morphology of fixed-beds is identified and similarities between industrial- and laboratory-scale modelling are discussed as well as defining the different sub-processes. Air distribution strategies and their effects on thermal conversion rates are also discussed.

Fixed-bed performance: Key quantitative measures of conversion efficiency such as burning rate, ignition speed and its rate, peak temperature and reaction zone thickness are defined and the most common methods to calculate these are discussed. A treatment of both particulate and gaseous species is also given.

Classification of bed models: Both micro- and macro-scale modelling are discussed as well as the general governing equations for the solid and gaseous phases. The spatial aspects of thermal conversion and its relation to homogeneity, assumed in the various models is identified.

Bed compaction characteristics: Key geometrical properties at the particle (unit density, particle size and shape) and bed level (volumetric surface area, porosity and shrinkage) are discussed.

Heat and mass transfer: Fuel properties (thermal conductivity, specific heat capacity and mass dispersion coefficient) as well as radiative heat transfer in fixed-bed combustion is discussed.

2. Fixed-bed configurations

2.1. Co-current and counter-current conversion

There are two types of fixed-bed configurations; co-current and counter-current conversion. The fuel typically exists in one of five states as it undergoes thermal conversion over time in either of these: green fuel (sometimes termed raw or virgin wood), dried particles, devolatilised particles then char and ash. The existence of the fuel over these different states results in a broadly stratified packed-bed with different fuel states and layers separated from each other through temperature. In co-current configurations, also traditionally known as gasification designs, the flame front propagates upward with the direction of oxidizer flow. Radiation and diffusion of heat flows have a relatively smaller influence because combustion starts at the bottom and heat and mass flow inside the bed is dominated by convective flow [19]. The advantages of this approach include: high heating value in gaseous products (flue gas) because of low oxidation, high conversion rates and ease of