Fuel 206 (2017) 638–656

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Simulating municipal solid waste incineration with a DEM/CFD method – Influences of waste properties, grate and furnace design

F. Wissing *, S. Wirtz, V. Scherer

Department of Energy Plant Technology (LEAT), Ruhr-University Bochum, Universitätsstraße 150, 44780 Bochum, Germany

ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form 30 May 2017
Accepted 7 June 2017

Keywords:
Modelling
Waste incineration
Combustion
Discrete Element Method (DEM)
CFD

ABSTRACT

The current work presents an initial approach of using a particle based method (Discrete Element Method, DEM) to simulate municipal solid waste (MSW) incineration on grates. Therefore, an in-house DEM code has been coupled with FLUENT. Models have been formulated for drying, volatile release and char conversion. The volatiles released are converted in the furnace above the waste bed which has been calculated with FLUENT. A comparison of simulations with measurements in an existing MSW incineration plant of CO_2, O_2, H_2O and temperatures above the bed is presented. Agreement is fair considering the measurement uncertainties and the complexity of the process. In a sensitivity study concerning the influence of waste composition (heating value, number of waste fractions), waste particle size distribution and radiative flux onto the waste bed on conversion has been carried out. Finally, the most common grate systems, backward stoking, forward stoking and roller grates have been compared briefly, including different types of furnace geometries above the bed. The results demonstrate that the approach developed gives new insight into the complex interaction of waste movement, waste conversion and gas phase combustion above the bed which can't be obtained with other approaches, like continuum models for the waste bed.

1. Introduction

In many industrialized countries legislation aims to reduce or even ban the further usage of landfills, since the disposal of municipal solid waste (MSW) is environmentally critical. Waste recycling is an option to reduce the amount of MSW to be disposed. For the remaining municipal waste, thermal treatment in incineration plants, producing heat and power, is the most common choice. Market estimations presume that 2200 waste incineration plants are in operation worldwide with a capacity of 280 million tons per day [1]. A further increase in capacity is expected with a focus in China.

The standard technology for waste incineration are grate firing systems, where the waste bed is transported over a grate by mechanical agitation with primary air passing in cross flow through the waste bed. Secondary air is added in the freeboard (furnace) above the bed (see Fig. 1). Grate firing systems have proven to be reliable and are robust in operation. Energy intensive MSW pre-treatment is not necessary which is an economic and ecologic advantage.

MSW grate firing simulations are a challenge, because the physical (humidity, density, size, shape) and chemical properties (elemental composition, heating value) of MSW vary in a wide range. The flow field and gas phase combustion above the waste bed can be predicted with sufficient accuracy with common CFD combustion models. The prerequisites are reliable boundary conditions of the species leaving the fuel bed. Therefore, the major uncertainty in MSW combustion simulation lies in an appropriate description of the fuel conversion within the waste bed.

Different approaches to model the fuel bed have been proposed. The most simple models are based on 1-dimensional approximations [2]. Thereby, the release of volatiles like C_xH_y, CO, CO_2, H_2O are pre-set based on a "typical" combustion progress on a grate while ensuring of an integral mass and energy balance. Bed internal processes are completely neglected. Suggestions to simulate MSW incineration by cascades of well stirred reactors have been made by Beckmann [3] and Gruber [4]. A coupling of a well stirred reactor cascade model with Star-CD has been presented by Appel [5]. The program CombAte [6,7] is another example of well stirred reactor cascades for MSW grate combustion. The fuel bed is subdivided into multiple stirred reactors in vertical and horizontal bed direction. Fuel bed mixing is accounted for based on grate- and plant-specific correlations. CombAte is real time capable and used for control purposes in an existing MSW plant.

* Corresponding author.
E-mail address: wissing@leat.rub.de (F. Wissing).

http://dx.doi.org/10.1016/j.fuel.2017.06.037
0016-2361/

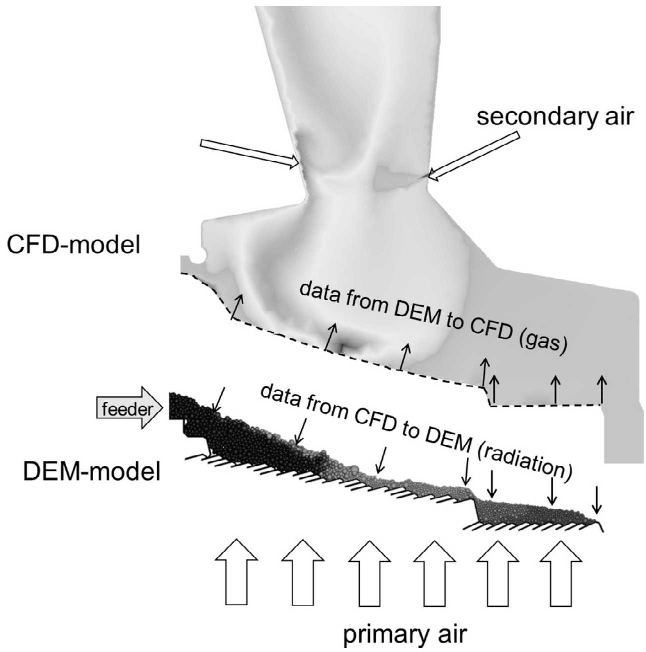

Fig. 1. Grate (DEM) and freeboard (CFD). Data exchange DEM/CFD coupling.

Continuum approaches go one step further in describing the fuel bed. Most of the development on continuum models for MSW grate combustion goes back to the work at Sheffield University. They formulated conservation equations for mass, momentum and energy (including radiation transport) for the gas and the solid phase within the waste bed. A semi-empirical correction term in the momentum equation for the solid phase accounts for bed mixing/stoking. The resulting 2D model of the waste bed, named FLIC, has been coupled with a CFD solver and was used to simulate grate firing systems (straw, wood chips, MSW) [8–13]. Another 2D continuum waste bed model coupled with CFD has been presented by Krüll [14]. He subdivides the waste bed into two different layers (bottom and top layer), both containing mass fractions of water, volatiles, fixed carbon and inert material to formulate a continuum approach for both layers. These two layers exchange solid mass based on an empirical stoking rate. In addition Euler-Euler approaches have been proposed for the combustion of granular assemblies. For example, Ryan and Hallet [15] used a respective approach to simulate packed bed combustion of char and Kurz et al. [16] applied it for the simulation of grate firing of wood chips.

All these models cannot reflect some major characteristics of grate firing systems and MSW. The fuel is transported along the grate by different stoking mechanisms (i.e. forward stoking, backward stoking or rollers) which define the transport velocity, but even more importantly, the mixing within the bed. This is important since, for example, fuel already ignited on the bed surface (towards the freeboard) can be mixed downwards into the fuel bed and serve there as local ignition sources. The MSW consists of multiple fractions (sanitary product, paper, wood, organic, textile, plastic, assembled package, leather, rubber, cork, inert) with very different physical and chemical properties, and, hence, different combustion and transport behaviors. The models introduced above typically only account for averaged fuel properties.

An option to resolve these drawbacks are particle based Lagrangian approaches [17–20]. In particular the Discrete Element Method [21] can form the basis of a particle based grate firing model. DEM allows the tracking of individual fuel particles of finite size, individual geometry and composition, as well as their mechanical interaction with each other and with moving walls (grate bars or rollers). The validity of DEM for the identification of the influence of stoking on mixing of spherical particles on grates has been shown by Sudbrock et al. [22,23]. This work has been extended by Rickelt et al. [24] in a DEM/CFD study to include the effect of convective heat transfer in grate systems.

Peters et al. [20,25,26] performed grate simulations based on a DEM/CFD coupling of spherical wood particles. DEM/CFD grate simulations for a domestic pellet stove have been presented by Wiese et al. [27] considering the actual cylindrical shape of pellets. Simsek [28] and Brosch [29] presented first results from a DEM/CFD coupling for MSW grate firing systems approximating waste fuel particles as spheres. A related DEM/CFD approach based on a representative particle model to simulate the incineration of radioactive Cs waste particles has been presented by Kuwagi et al. [30].

The current paper is an extension of our previous work on grate systems [24,27–29]. Its novelty lies in the application of DEM/CFD simulations to model waste incineration plants. In particular, we will present a sensitivity study concerning the representation of fuel properties (5 fractions versus 11 fractions, variation of mean waste heating value and particle size distribution). Furthermore, differences between the combustion on forward stoking, backward stoking or roller grates in combination with different freeboard configurations will be discussed.

Note that the individual shape of each waste particle cannot be represented in DEM, this is far out of reach in terms of model formulation and computing time. It is even not a constructive approach, because the actual shape of waste particles is essentially not known. However, characteristic statistical parameters like particle size distribution must be accounted for, and also the characteristics of the bulk movement of waste must be mimicked by appropriate assumptions. In fact, in the current DEM simulation the fuel particles are represented as spheres, where the sphere dimensions represent the area of mechanical influence of a specific fuel particle rather than its actual geometry. The further philosophy behind this approach will be discussed later in the paper.

The authors are well aware that the particle based approach presented has still severe limitations, but it goes beyond continuum models or Euler-Euler-formulations.

2. The simulation procedure

An in-house Discrete Element Method (DEM) code [31,32] is applied, to describe the particle motion and conversion as well as the gas phase reaction within the waste bed. Interaction and segregation effects within the fuel bed and also transport and mixing induced by mechanical agitation are directly simulated by DEM. The flow field and the homogeneous gas phase reactions (of the volatiles leaving the waste bed) in the freeboard are described using standard sub-models of the commercial CFD software package ANSYS FLUENT. Note that the in-house DEM code coupled with CFD has already been used to simulate lime shaft kilns [33], drying on grates [34], pellet stoves [27] and also a first approach to simulate MSW incineration [28] has been presented. Therefore, we restrict the description of the methodology to a minimum and refer for further details to [27–29].

2.1. Particle and fluid phase coupling

The time scales of heterogeneous reactions in the waste bed and the gas phase reactions in the freeboard above the bed are very different. Heterogeneous reactions are slow, whereas gas phase reactions are fast. Therefore, we use a transient DEM simulation and couple it with a steady-state FLUENT flow field simulation above the bed.