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Discrete element analysis of experiments on mixing and bulk transport of wood pellets on a forward acting grate in discontinuous operation

H. Kruggel-Emden [a,*], Rimantas Kačianauskas [b]

[a] Ruhr-Universitaet Bochum, Universitaetsstrasse 150, D-44780 Bochum, Germany
[b] Institute of Mechanics, Vilnius Gediminas Technical University, st. J. Basanavičiaus, LT-10223 Vilnius, Lithuania

H I G H L I G H T S

- ▶ Mixing and bulk transport on a model type forward acting grate was investigated.
- ▶ Simulations by the discrete element method (DEM) were performed.
- ▶ An acceptable agreement is found between DEM-simulations and experiments.
- ▶ Deviations are apparent for the final mass on the grate and the discharge rate.
- ▶ Results enable DEM to be used for reacting particles of complex shape in the future.

A R T I C L E I N F O

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A B S T R A C T

Grate systems are of significant importance in many energy technology applications, where heterogeneous fuel like biomass which is composed of non-spherical particles of varying sizes is processed. Particulate solid mixing and transport on a grate have direct influence on the thermal conversion process. Therefore, a detailed understanding of the mixing and transport of the particulate solid is essential for the further development of biomass and waste incineration plants. The discrete element method (DEM), in which all particles and their interactions are tracked over time, allows obtaining in-depth information on mixing and bulk transport on grate systems and provides an easy way to avoid extensive experimental investigations. Up to now, grate systems have mainly been addressed by the discrete element method for particles of spherical shape. In the current paper simulations with the discrete element method of a scale model of a forward acting grate are performed neglecting particle/gas interaction, heat and mass transfer as well as chemical reactions. The grate is operated discontinuously with cylindrical shaped wood pellets applied as bed material. Different motion patterns and grate operational conditions are investigated. The particle motion and the mixing are monitored through image analysis and the discharged particle mass is analyzed. The obtained results indicate a reasonable agreement of simulations and experiments, and show that the discrete element method is capable of predicting mixing and bulk transport on grate systems.

1. Introduction

Grate systems are of significant importance in many energy technology applications, where mixing and transport of particulate solids are required. Especially for the thermal conversion of heterogeneous materials, such as waste or biomass, grates are highly suited as they allow the processing of particulate solids with inhomogeneous composition and strong size variations. Very often grates are equipped with movable bars which ensure the transport of the particulate solid and provide the necessary agitation to initiate mixing. A detailed review on grate incineration systems was published by Yin et al. 2008.

Grate combustion systems can be readily improved besides experimental investigations through numerical methods. Thereby, both adequate fuel bed models must be combined with a precise description of flow and reactions in the combustion chamber (Simsek et al., 2009). An important feature of a fuel bed model is the ability to correctly represent the particulate solid mixing and transport. In many state of the art numerical models the fuel bed is still represented by relying on empirical models or by

* Corresponding author. Tel.: +49 234 32 27362; fax: +49 234 32 14 227.
E-mail address: kruggel-emden@leat.rub.de (H. Kruggel-Emden).

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introducing severe simplifications. Empirical models (Dong and Blasiak, 2001) have the disadvantage to be grate specific and are thereby not well suited for numerical studies on optimal grate operation parameters or variations in the grate design. Alternatively, the fuel bed is often modeled through a cascade of ideally stirred zero or one dimensional reactors (Wurzenberger et al., 2002), where the former neglect differences in varying bed depth and the latter still represent mixing insignificantly as they rely on empirical assumptions such as solid diffusion coefficients (Lim et al., 2001; Yang et al., 2005; Kruell, 2001). Additionally, a predefined bed velocity has to be assumed for the fuel bed. More advanced models describe the fuel bed as a multidimensional continuum (Kurz et al., 2011) which relies on the Navier-Stokes equations in which the viscosity and the pressure in the granular phase is calculated from the kinetic theory of granular flow (Ding and Gidaspow, 1990). Though, continuum based fuel bed models are often solved with simplifications – the horizontal bed velocity is usually predefined and vertical mixing is derived through empirical closures (Kruell, 2001; Kær, 2004; Goh et al., 2001).

In contrast to continuum models, discrete models like the discrete element method have the advantage to not rely on empirical closures and to be capable to fully represent the mechanical behavior of the fuel bed. In discrete approaches (Zhu et al., 2007, 2008) all particles and their interactions are represented over time. Especially for small and moderate scale systems discrete approaches are well suited. Up to now, grate systems have been mostly addressed by discrete approaches for particles of spherical shape (Simsek et al., 2009; Peters et al., 2005; Džiugys et al., 2006, 2007; Džiugys and Navakas 2009; Kruggel-Emden et al., 2007; Sudbrock et al., 2011) – wood pellets, as non-spherical particles, have been considered by Kruggel-Emden et al., 2012 on a simplified vertically oriented model type grate without feeding and discharge, recently.

The discrete element method is well suited to model complex shaped particles (Höhner et al., 2011) – nonetheless not many simulations involving grate systems have been performed so far. Therefore, the goal of the current study is to check whether discrete element simulations are suited to predict the mixing and transport behavior of complex shaped particles on grates. Experimental data is considered from an anterior study by Kruggel-Emden et al. 2013. As non-spherical particles wood pellets of a defined length distribution are considered which are colored to distinguish between different layers in the investigations. As grate system, a forward acting grate is utilized which discharges initially placed particles in discontinuous operation. Operational parameters are varied and the influence on the particle mixing and transport is evaluated based on the discharged mass and a subsequently performed image analysis in simulations and experiments.

2. Numerical method

As numerical framework the discrete element method is applied which is often utilized for systems of particles with spherical shape (Zhu et al., 2007, 2008). When the discrete element method is used to represent non-spherical particles, the translational motion is obtained by integrating Newton's equations of each particle in the inertial frame which is fixed and not moving with the particle

$$m_i \frac{d^2 \vec{x}_i}{dt^2} = \vec{F}_i + m_i \vec{g}, \tag{1}$$

with particle mass m_i, particle accelerations $d^2\vec{x}_i/dt^2$, contact forces $\vec{F}_i$ and gravitational forces $m_i\vec{g}$ (Kruggel-Emden et al., 2008). The rotational motion must obey the Euler equations in the body fixed frame (Kruggel-Emden et al., 2008) which is placed in the center of gravity of a particle and coincides with its principal axes of inertia

$$\hat{I}_i \frac{d\vec{W}_i}{dt} + \vec{W}_i \times (\hat{I}_i \vec{W}_i) = \Lambda_i^{-1} \vec{M}_i, \tag{2}$$

where $d\vec{W}_i/dt$ is the angular acceleration, $\vec{W}_i$ the angular velocity in the body fixed frame, $\vec{M}_i$ the external moment resulting out of contact forces in the inertial frame, $\hat{I}_i$ the inertia tensor along the principal axis and Λ_i^{-1} the rotation matrix converting a vector from the inertial frame into the body fixed frame. The translational motion of the particles is solved by a Runge-Kutta-scheme and the rotational motion through an explicit scheme being based on the algorithms proposed by Munjiza et al., 2003 and Johnson et al., 2008.

The wood pellets are represented by the multi-sphere method by approximation of their cylindrical shape through a sufficient number of spheres with fixed relative position to each other. The length distribution of the wood pellets available for investigation is outlined in Fig. 1a.

The mean length is l=13.2 mm; smallest particles are l_{min}=4.0 mm and largest l_{max}=25.0 mm. In the discrete element simulations the real particle length distribution (black line) is represented by four length classes (blue line) as shown in Fig. 1a. Such an approximation of shape through a limited number of representative length classes is favorable to limit computational effort and has been tested successfully for wood pellets in a previous investigation (Kruggel-Emden et al., 2012). The spherical particles used for the approximation of the wood pellets have a diameter of d=8.0 mm which equals the diameter of the wood pellets. For the length class of l=8 mm only one sphere, for l=13.2 mm and l=17.9 mm three spheres and for l=22.2 mm four spheres are used as approximation as shown in Fig. 1a. Thereby, pellet lengths sizes of below 8 mm which have a proportion

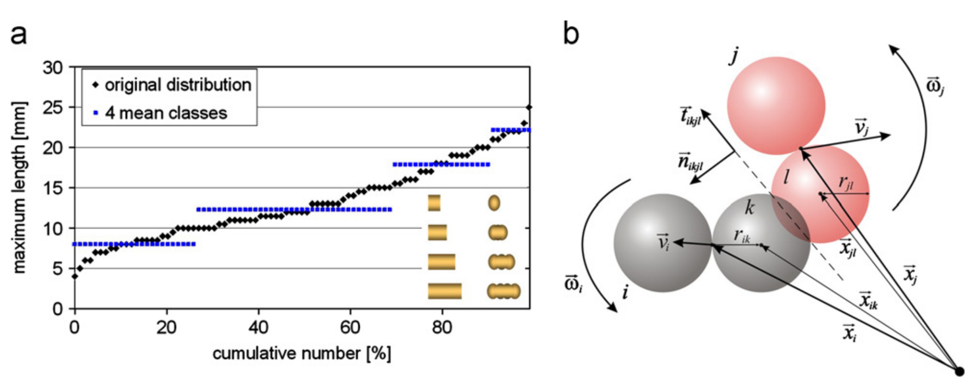

Fig. 1. (a) Pellet length distribution and their approximation by the multi-sphere approach and (b) collision of two pellet shaped particles. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)