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An experimental investigation of mixing of wood pellets on a forward acting grate in discontinuous operation

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ABSTRACT

The knowledge about mixing and the transport efficiency of non-spherical particles on grates is needed for the improvement of design and adaption of operational parameters in grate combustion systems. To gain insight into details of the transport of non-spherical particles experimental investigations with a scale model of a forward acting grate are performed in discontinuous operation using wood pellets as bed material. Wood pellets are an important source of biomass within an energy market increasingly relying on renewable sources.

Different motion patterns, grate operational conditions and pellet types are investigated. A comparison to spherical particles is performed. The wood pellets as well as the spherical particles are dyed in different colors to distinguish between different layers applied vertically and horizontally on the grate. The particle motion and the mixing are monitored by image analysis from the top and the side of the grate through transparent walls. In addition the discharged particle mass is recorded. The particle mass, the stroke length as well as the particle shape and the motion pattern have a strong influence on the mixing. The stroke velocity only has minor effect on mixing and the amount of particles discharged from the grate. The results obtained under well established boundary conditions are suitable for use as reference data in the verification of particle based simulation approaches as, e.g. the discrete element method.

1. Introduction

The demand for renewable energy is expected to grow considerably within the next years. This encompasses wind and solar energy but also impacts the utilization of solid biomass. A convenient and economic way to provide solid biomass is through the pelletizing of wood residuals. State of the art studies on wood pellet consumption [1] expect a strong increase in wood pellet production and usage within the EU from 10 million tons in 2010 up to 105–305 million tons in 2020. Different process options for the thermal utilization of biomass provided in the form of wood pellets [2] do exist. Pellets may be milled and co-fired with conventional fossil fuels—thereby the pellets can only substitute a fraction of the fossil fuels (less than 25% on energy basis). As alternative fluidized bed combustion or grate firing systems are applicable which are robust in their operating behavior. Especially grate firing systems allow the processing of heterogeneous solid materials involving a wide range of particle sizes of inhomogeneous composition. These characteristics make grate firing systems very widely used in a broad range of performance categories ranging from 6 kW_{th} up to 1200 MW_{th} [2].

In grate firing systems the solid fuel is supplied by a feeding system onto the grate. The grate transports the fuel while it is being incinerated and supplies a part of the required air (primary air) for the combustion process. Different grate designs (stationary sloping, traveling, reciprocating and vibrating grates) are available and allow to control the combustion process to different extends. Especially reciprocating grates which are composed of bars that can be operated in forward or backward mode allow a precise control of the combustion process by the ability to intensely mix the bed material. The grate is cooled through the primary air or sometimes water cooling is used for additional heat removal. In the combustion chamber above the grate the volatiles released from the fuel bed are burned by additionally supplied air (secondary air). By adjusting the amount of primary and secondary air, the overall temperature, and thereby the grate combustion process, is controlled to emit low amounts of pollutants such as nitrogen oxides and others [2].

An improvement of grate systems is, besides experimental investigations, possible through numerical methods. Thereby the challenge for numerical methods is the modeling of the reacting fuel bed on the grate and its interaction with processes in the combustion chamber during thermal conversion. The simplest way to model grate systems is the use of experimentally or empirically gained correlations [3]. These simplistic models are based on coarse mass and energy balances and only provide information on the fuel conversion and the released volatiles as a function of the position along the grate length. In certain cases these empirical models may lead to acceptable representation of

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relevant phenomena on the grate however their main limitation is that they are grate specific and thereby not well suited to represent variations in the operational parameters [4]. Alternatively the fuel bed can be represented as a cascade of stirred reactors [5]. Under the assumption of a predefined bed velocity the fuel is transported from reactor to reactor along the grate. Thereby important aspects of the grate combustion as differences in the temperatures, of the fuel conversion or of the volatiles released in different bed depths are not covered. In order to overcome these limitations the fuel bed can be modeled as multidimensional continuum [4] or as a discrete particle assembly [6,7].

Continuum models for the fuel bed are based on the Navier–Stokes equations in which the viscosity and the pressure of the granular phase are calculated from the kinetic theory of granular flow [8]. Models derived from the kinetic theory are from their concept so far not applicable to systems of non-spherical particles [9]. Systems of arbitrary shaped particles are therefore difficult to handle in a continuum framework based on the kinetic theory of granular flow—instead the underlying partial differential equations are often solved with severe simplifications. The horizontal bed velocity is often predefined and, for the vertical mixing, empirical models find application [10–12]. In contrast discrete modeling approaches like the discrete element method [13] have the advantage not to rely on severe model simplifications or assumptions and to be capable to accurately represent the mechanical behavior of the bed. Thereby the overall motion of the particle system is based on the single particle behavior and the interaction of all particles on the grate over time. Especially for systems of moderate scale the discrete element method is well suited and a promising simulation approach [14]. Up to now grate systems have been only addressed by the discrete element method for particles of spherical shape [6,15–21]. Within the discrete element method varying methods for shape approximation are available [22]; however to validate their suitability for grate systems involving complex shaped particles, experimental reference investigations under well defined boundary conditions are necessary which are scarce in scientific literature. With validated discrete element models a broad range of grate design specifications as well as operation parameters can be readily investigated and may help improve grate design, grate operation or may form the basis for the improvement of macroscopic models.

Artificial complex shaped particles (cubes) have been experimentally considered for different small grate systems by Lim et al. [23] and a stochastic model has been derived. Džiugys et al. considered residence time distributions of wood chips [16] and a mixture of wood chips and clay particles [17] on a forward acting grate and compared results qualitatively with two-dimensional simulations involving spherical particles. Spheres have also been extensively investigated on a vertically oriented model type grate by Sudbrock et al. [21] neglecting feeding and possible discharge. Municipal solid waste was experimentally investigated by Nakamura et al. [24] on a large scale reverse acting grate by applying differently sized spherical tracer particles and deriving a two dimensional grate specific model.

As most of the investigations listed partly neglect complex shaped particles or are not carried out under well defined boundary conditions, the current work addresses such a system. As particle system, wood pellets of well defined length distribution and diameter are considered which are colored to distinguish between different layers. For comparison spherical particles are applied. A forward acting grate with fixed inclination is utilized and operated without feeding system in discontinuous operation. Note that such an operation mode does not reflect the characteristics of the operation of a realistic grate system. Instead, it opens up the opportunity to apply well reproducible conditions easily applicable in simulations. Operational parameters are varied and the influence on the mixing and transport properties is evaluated based on the discharged mass and a subsequently performed image analysis of photos recorded from the top and the side of the grate.

2. Experimental investigation

In the following details on the experimental setup, the experimental procedure and the investigated parameters are given.

2.1. Experimental setup

The experimental rig is designed as a forward acting grate with a fixed inclination (Fig. 1). It consists of 16 equally aligned polypropylene bars where bars with an uneven number are fixed and bars with an even number are movable and are capable of actively agitating the bed material. Details on the dimensioning of the rig in initial configuration are provided in Table 1.

Each bar of the grate is of a length of 160 mm, of a height of 40 mm and of a depth of 110 mm. Each bar is equipped with a 45° bezel of an edge length of 12 mm. The grate is mounted on top of a massive metal plate of length 1055 mm. In the vicinity of the discharge gap close to bar 1, the metal plate is coated with polypropylene to ensure uniform surface properties. The grate is inclined by 16° which is a typical value for an industrial forward acting grate. To the front and back the grate is encased by two transparent polycarbonate walls. The bars of the grate are supported by rods of length f^1–f^{16} ranging from 40 to 865 mm. The rods attached to movable bars are connected to linear motors (LH11) manufactured by Phoenix Mecano. The linear motors are controlled by a Siemens SIMATIC OP17.

Different moving modes have been programmed into the SIMATIC OP17 where the two moving modes “same” and “opposite” outlined in Fig. 2 are considered in the investigation here. Bars are movable with a stroke velocity of up to 15 mm/s and the stroke length can be adjusted up to 40 mm. At the turning points the bars pause for 1 s. The SIMATIC OP17 controller allows to interrupt the bar movement after each combined back and return movement at the lower return point for an arbitrary length of time.

Two PANASONIC NV-GS230 3CCD cameras are positioned 1.8 m in front and 1.5 m atop of the grate and provide single images of 1760×1320 pixels in top and side view of the grate. An object length of 1 cm is roughly captured by 14 pixels. The particles used in the investigation are wood pellets (Power Pellets) of a diameter of 8 mm and 6 mm (Fig. 3a) with a length distribution as shown in Fig. 3b. To investigate the effect of particle shape additionally equally sized spherical wood particles with a diameter of 10 mm are considered which have the same volume as the averaged volume of the pellets with 8 mm diameter. Roughly 200–400 particles are visible from the side or the top. For their distinction in the experiments the particles are dyed in green, red and yellow with NIGRIN spray paint.

The material properties of the wood pellets and spheres, bars and walls are listed in Table 2, while the collision parameters derived according to the procedure outlined in [21] are given in Table 3. The applied spray paint does not alter the derived contact parameters—the results obtained in the following are therefore fully transferable to untreated pellets as used in energy technology applications.

2.2. Experimental procedure

Experiments are performed with particles colors aligned in series (Fig. 4a) or in stacked configuration (Fig. 4b). In the configuration where particles are aligned in series, division bars placed at the bezels of the first, sixth and eleventh grate bar prevent slipping of the wood pellets during the initial placement of the particles. The particles were inserted by hand forming a uniform layer. The division bars are aligned parallel to the front section of the grate bars as shown in Fig. 4. After the particles have settled the division bars are removed carefully. The dyed particles are always arranged such that red particles are put atop yellow particles and yellow particles atop green particles. The total pellet mass is equally distributed among the red, yellow and green particles in all experiments.