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Review paper

Review and benchmarking of process models for batch screening based on discrete element simulations ☆

Frederik Elskamp, Harald Kruggel-Emden *

Ruhr-Universitaet Bochum, Universitaetsstrasse 150, D-44780 Bochum, Germany

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A B S T R A C T

In the recent past detailed particle-based simulation approaches such as the discrete element method (DEM) have become popular in addition to phenomenological models for the design and optimization of operating parameters of screening processes. As phenomenological process models, a large number of probabilistic and kinetic approaches of differing complexity are available which mostly provide information on the screening rate or efficiency. So far a review and comparative benchmarking of the various available screening process models has not been performed, although they are of high relevance, especially in industrial applications, due to their simplicity and easy use. To perform the benchmarking of batch screening process models, it is not relied on experimental investigations, but on detailed DEM-simulations involving both spherical and non-spherical particles in the investigation here. The DEM-simulations allow examining different particle characteristics such as size, shape, friction, as well as overall mass and size distribution. In addition, screen characteristics such as screen dimensions and surface as well as operational parameters including vibration frequency, stroke angle and amplitude are considered. On the basis of the DEM-simulations screening efficiencies are obtained which allow the adjustment and thereon benchmarking of the process models through parameters such as the residual particle mass on the screen.

Contents

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* Corresponding author. Tel.: +49 234 32 27362; fax: +49 234 32 14227.
E-mail address: Kruggel-Emden@leat.ruhr-uni-bochum.de (H. Kruggel-Emden).

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1. Introduction

In many processes in materials preparation technology, mechanical process engineering, mineral processing and energy technology individual particles of various bulk materials are often of non-spherical shape and broad size distribution [1,2]. Here, it is frequently required to separate a particulate solid into sub-products with different particle size ranges as e.g. in mineral processing when crushed material is separated into crushed rock, gravel and sand. Alternatively, it is sometimes essential to remove dust or abrasion products from coarser grained materials. If a multi component bulk solid mainly differs in particle size, it is regularly required to split up its components by size as e.g. done in grain processing and food related processes. Furthermore, it is occasionally required to separate bulk solids comprising of similarly sized, but differently shaped particles. All these tasks can be performed by the simple process step screening which in industry is mostly regarded as mature. Nevertheless, scientifically screening and its sub-processes are currently still not satisfactorily understood, often complicating the design and optimization of screening processes in both small scale laboratory and industrial applications.

For the design and optimization of screening processes particle-based simulation approaches such as the discrete element method (DEM) dating back to Cundall and Strack [3] and Walton and Braun [4] as well as various phenomenological models are available. By providing a detailed insight into screening processes the DEM allows, after appropriate validation of its model parameters, the optimization of equipment and operating parameters without performing extensive experimental investigations. DEM-simulations are predictive and due to their transient nature, dynamic processes associated with screening such as segregation, passage and transport are represented, inherently.

The first application of the DEM towards screening dates back to Shimosaka et al. [5], who performed three-dimensional simulations on a batch-operated screen with a small number of particles (400 particles) and used the simulations to derive a phenomenological screening model. In further continuous screening investigations the influence of the single particle size, particularly of larger or near aperture size particles and of the whole thickness of the bulk particle layer on the screening efficiency were considered [6,7]. Moreover, a small scale, three-dimensional screen with periodic boundary conditions was investigated by Cleary [8]. Large scale screens were addressed in the works of Dong et al. [9], Alkhaldi and Eberhard [10] and Chen et al. [11]. The accuracy that is needed to represent the complex screen surface was studied by Alkhaldi et al. [12]. For realization of significant savings in computation time stochastic models were applied, whereby accuracy is lost. Up to now, particles of complex shape were only addressed in few numerical investigations involving the DEM in the context of the process step screening [13,14]. In particular, Delaney et al. [15] concluded that deviations for the transport of the bulk material as well as for the segregation and passage behavior of the near aperture size particles are evident if complex-shaped material is not modeled by complex-shaped particles in simulations. Motivated by Ref. [15], the influence of particle shape on continuous screening was studied numerically by Kruggel-Emden and Elskamp corroborating this behavior [16].

Over the last years several investigations were performed of screening processes based on the DEM. Circularly vibrating screens have been studied by Zhao et al. [17] with regard to the vibration amplitude, throwing index and screen inclination; based on the simulations recommendations towards optimal operational parameters were proposed. Extending investigations by Alkhaldi et al. [12], Tung et al. [18] focused on the effect of the woven-mesh structure in batch screening investigations. Further studies addressed banana screens [19], or other continuous screening processes in which especially the screen agitation was varied [20–22]. Very recently, particle/fluid interaction as well as adhesive forces due to liquid bridges were considered in DEM-simulations of screening processes [23–25].

The listed investigations clearly indicate that the DEM is capable of providing detailed insight into screening processes. The DEM was validated against experimental data [26] and proved successful and reliable [16]. In case that no interstitial fluid is of relevance [27], no further model parameters, beside the contact parameters, are required to perform meaningful simulations. The DEM is thereby suited for optimization of equipment and operating parameters [6,7,16,17,20–22] or applicable for deriving and verifying simpler and less computationally extensive phenomenological models without performing extensive experiments as demonstrated firstly by Shimosaka et al. [5].

In the present work addressing batch screening processes involving spherical and non-spherical particle shapes, phenomena such as particle passage and the residual mass over time are investigated in detail. These investigations form the basis to use DEM-simulations reliably for a comparative study of phenomenological batch screening process models following the idea of Shimosaka et al. [5]. The article is structured as follows. In Section 2 the numerical method is described, followed by a description of the considered screening process models in Section 3. The numerical setup and the applied simulation parameters are outlined in Section 4. Results in Section 5 firstly address different batch simulations, before the particle passage behavior is compared to the outcome of various phenomenological screening process models.

2. Numerical method

The DEM can be applied to systems of particles with non-spherical shape [28,29] by obtaining the translational and rotational motion of each particle. For this purpose the Newton's and Euler's equations are integrated

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

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

with particle mass m_i, particle acceleration $d^2\vec{x}_i/dt^2$, contact force $\vec{F}_i$, gravitational force $m_i\vec{g}$, angular acceleration $d\vec{W}_i/dt$, angular velocity $\vec{W}_i$, external moments resulting out of contact forces $\vec{M}_i$, the inertia tensor along the principal axis $\hat{I}_i$ and the rotation matrix converting a vector from the inertial into the body fixed frame Λ_i^{-1}. Both equations (Eqs. (1) and (2)) are solved by explicit integration schemes [30].

A flexible approach to model complex shaped particles in the DEM is the multi-sphere method where arbitrary sized spheres are clustered to resemble the desired complex particle shape [31]. In this method contact force laws as used for spherical particles are applied [32]. Further details on the contact scheme involving clustered spheres can be found in Refs. [33,34]. A sketch of two simple colliding particles *ik* and *jl* is shown in Fig. 1.

The normal component of the contact forces is obtained from a linear spring damper model

$$\vec{F}^n_{ikjl} = k^n \cdot \delta_{ikjl} \cdot \vec{n}_{ikjl} + \gamma^n \cdot \vec{v}^n_{ikjl}, \tag{3}$$

where subscripts *i*, *j*, *k* and *l* represent the four different spheres of the two particles *ik* and *jl*, k^n is the spring stiffness, δ_{ikjl} the virtual overlap, $\vec{n}_{ikjl}$ a normal vector, γ^n a damping coefficient and $\vec{v}^n_{ikjl}$ the normal velocity in the contact point. Both k^n and γ^n determine the