Minerals Engineering 83 (2015) 78–96

Contents lists available at ScienceDirect

Minerals Engineering

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

Benchmarking of process models for continuous screening based on discrete element simulations

Frederik Elskamp [a], Harald Kruggel-Emden [a,*], Manuel Hennig [b], Ulrich Teipel [b]

[a] Ruhr-Universitaet Bochum, Universitaetsstrasse 150, D-44780 Bochum, Germany
[b] Technische Hochschule Nürnberg Georg Simon Ohm, Wassertorstrasse 10, D-90489 Nuremberg, Germany

ARTICLE INFO

Article history:
Received 8 April 2015
Revised 7 August 2015
Accepted 13 August 2015
Available online 27 August 2015

Keywords:
Continuous screening
Discrete element method (DEM)
Arbitrary shaped particles
Process models

ABSTRACT

For the design and the scale-up of screening processes and the optimization of operating parameters the particle-based discrete element method (DEM) as well as classic phenomenological screening models are available. Phenomenological screening process models are simple to use and require only sparse computational resources, hence providing the possibility to use them efficiently in industrial applications. In this context, a comparative benchmark of numerous kinetic and probabilistic screening models of various complexities has been performed for discontinuous screening, recently. Following the approach of this study, in the investigation here, DEM-simulations applying spherical and non-spherical particles are used to benchmark process models for continuous screening. In the DEM-simulations different particle characteristics such as size, shape and size distribution are taken into account. Screen characteristics such as aperture size, wire shape and inclination angles as well as operational parameters including vibration frequency, amplitude, stroke angle and mass flow rate are varied. Based on the data obtained from the simulations, the overall fraction retained on the screen as well as the selectivity in terms of overflow partition number, the transport velocity and the residence time all in dependence on particle size are investigated. Finally, phenomenological screening process models are adjusted to the outcome of the DEM-simulations in terms of the fraction retained on the screen and overflow separation curves, respectively. The resulting deviations are evaluated and thereby allowing the comparative benchmarking of available process models for continuous screening. Obtained DEM-results indicate a strong dependence of screening on operational parameters and particle shape. Screening process models vary intensively in their ability to represent DEM-results.

1. Introduction

Screening or sieving is a technical simple, but important process step widely used in industry for the classification of particles. In mechanical process engineering, materials preparation technology or energy technology it is routinely used to separate various bulk materials consisting of particles with sometimes broad size distribution according to desired size class specifications. Such particles are usually of non-spherical shape complicating the separation into homogeneous classes (Grozubinsky et al., 1998; Liu, 2009). Besides separating crushed material into sub-products in minerals engineering, screening is applied for a wide range of tasks including e.g. the removal of dust or wear debris from coarser grained materials, splitting up components in grain processing or in other food related processes according to particle sizes or the separation of similarly sized particles by their shapes. Despite its widespread usage in industry, the scientific understanding of screening is still not completely matured, often leading to complications when designing, optimizing or scaling-up screening processes.

To overcome current limitations in the understanding of screening without performing extensive experimental investigations, the discrete element method (DEM) dating back to Cundall and Strack (1979) and Walton and Braun (1986) as a particle-based simulation approach is applicable. DEM-simulations are predictive and provide detailed insights into screening processes, giving the possibility to study the governing dynamic sub-processes such as particle transport, stratification and passage. This knowledge is essential when optimizing equipment and operating parameters.

Documented experimental studies of screening date back to the first part of the last century (Gaudin, 1939). However, the first DEM screening investigations addressing small scaled batch-operated screens are reported for the beginning of this century (Shimosaka et al., 2000). The influence of the particle layer thickness on screening efficiency for continuous screening was analyzed by Li et al. (2002) followed by investigations of the differing behavior of

---

[*] Corresponding author.
E-mail address: kruggel-emden@leat.ruhr-uni-bochum.de (H. Kruggel-Emden).

http://dx.doi.org/10.1016/j.mineng.2015.08.011
0892-6875/

near mesh sized and oversized particles (Li et al., 2003). In the works of Alkhaldi and Eberhard (2007) and Chen et al. (2010) large scale screens were studied, whereas Cleary (2004) diminished the effort required to simulate a screen with the help of periodic boundary conditions. The required accuracy for modeling the sieve wire structure was addressed by Alkhaldi et al. (2008), Tung et al. (2011) and Kruggel-Emden and Elskamp (2014). Investigations addressing the particle excitation on the screen induced by various stroke orientations, amplitudes and inclination angles were performed by Zhao et al. (2011), H. Dong et al. (2013) and Xiao and Tong (2012, 2013). Further studies addressed banana screens operated with dry particles (Dong et al., 2009; Liu et al., 2013), particle/fluid interaction as well as adhesive forces due to liquid bridges on screens (Dong and Yu, 2012; Li et al., 2012) and banana screens simulated under wet conditions (Cleary et al., 2009a,b; Fernandez et al., 2011).

Evident deviations for the stratification and the passage of near mesh sized particles as well as for the particle transport occur if non-spherical bulk material is modeled by spherical particles in simulations (Delaney et al., 2012). Nevertheless, up to now, only a few numerical investigations of screening processes involving complex shaped particles were carried out (Cleary et al., 2009a,b; Elskamp and Kruggel-Emden, 2015; Kruggel-Emden and Elskamp, 2014).

For screening processes with dry particles, the DEM was validated against experimental data (Hilden, 2007) and proved successful and reliable (Kruggel-Emden and Elskamp, 2014). Therefore, the DEM is an appropriate tool to optimize operating parameters and appliances (H. Dong et al., 2013; Kruggel-Emden and Elskamp, 2014; Li et al., 2002, 2003; Xiao and Tong, 2012, 2013; Zhao et al., 2011). Additionally, the derivation and verification of simpler and less computational demanding phenomenological models without performing extensive experiments is feasible. First, this was demonstrated by Shimosaka et al. (2000) for batch screening processes and very recently by K.J. Dong et al. (2013) for continuous screening.

In a former publication by the authors (Elskamp and Kruggel-Emden, 2015) batch screening processes were investigated in detail and a benchmarking of applicable phenomenological screening process models was performed. In the present study continuous screening involving spherical and non-spherical particle shapes is addressed. Therein, phenomena such as particle passage, average transport velocity in dependence on particle size and the residual mass flow over the screen length are investigated in detail. These investigations form the basis to use DEM-simulations reliably for a comparative study of phenomenological continuous screening process models as previously performed for discontinuous screening (Elskamp and Kruggel-Emden, 2015).

The article is divided into five sections. Sections 2 and 3 are the description of the numerical method and of the considered steady state screening process models, respectively. Section 4 addresses the numerical setup and the applied simulation parameters. Besides particle transport velocities, residence times and results of the particle passage behavior for continuous screening are shown in Section 5.1. Afterwards, a comparison is made between the passage in dependence on screen length and particle size, respectively, to the outcome of various phenomenological screening process models in Section 5.2 (spatially resolved models) and Section 5.3 (separation curve models). Finally, conclusions are drawn in Section 6.

2. Numerical method

Besides spherical particles, the DEM can be applied to systems with non-spherical shaped particles (Zhu et al., 2007, 2008). For this purpose the translational and rotational motion of each particle are tracked by integrating the Newton's and Euler's equations

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

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

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 (comp. e.g. (Munjiza et al., 2003)).

The multi-sphere method is a flexible approach to model complex shaped particles in the DEM. Thereby, the desired complex particle shape is resembled with clustered arbitrary sized spheres (Kruggel-Emden et al., 2008a) applying similar contact force laws as used for spherical particles (Höhner et al., 2011).

Fig. 1 shows a sketch of two simple colliding complex particles i and j, where the spheres l and k got into contact. Further details on the contact scheme involving clustered spheres are provided in Kruggel-Emden and Kačianauskas (2013) and Kruggel-Emden et al. (2012).

The normal component of the contact forces is obtained from a linear spring damper model which is exemplarily given for the contacting spheres k and l of particle i and j as

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

where 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 at the contact point. Both k^n and γ^n determine the coefficient of normal restitution between particles e^n_{PP} as well as between particles and walls e^n_{PW} (Kruggel-Emden et al., 2007). For the calculation of the tangential forces a linear spring limited by the Coulomb condition is applied

$$\vec{F}^t_{ikjl} = -\min\left(k^t \cdot |\vec{\xi}_{ikjl}|, \mu_C \cdot \left|\vec{F}^n_{ikjl}\right|\right) \cdot \vec{t}_{ikjl}, \tag{4}$$

where k^t is the stiffness of a linear spring, μ_C is the friction coefficient, $\vec{\xi}_{ikjl}$ is the relative tangential displacement and $\vec{t}_{ikjl}$ is the tangential unit vector (Kruggel-Emden et al., 2008b).

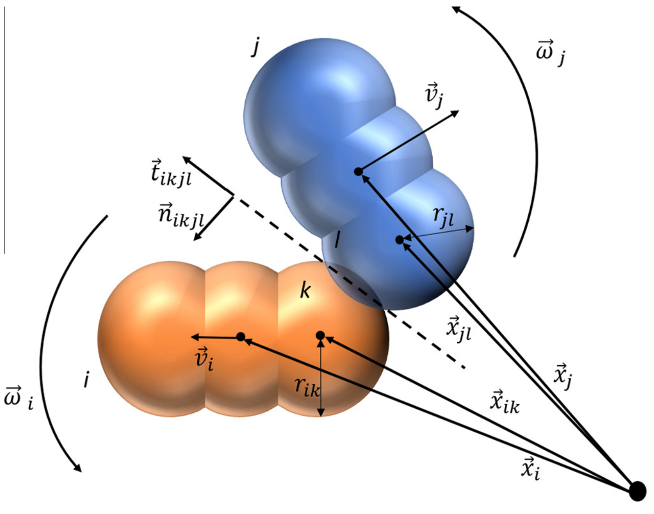

Fig. 1. A collision of two multi-sphere particles.