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Effect of particle shape on flow in discrete element method simulation of a rotary batch seed coater

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ABSTRACT

In the seed processing industry, rotary batch seed coaters are widely used for providing a protective coating layer (consisting of various ingredients including fertilisers and crop protection chemicals) on the seeds. Seed motion and mixing are important in ensuring uniform coating. In the rotary batch seed coater, the base of a cylindrical vessel rotates, whilst the cylindrical wall is stationary and two baffles turn the bed over for mixing. In the present study, the Discrete Element Method (DEM) is used to simulate the effect of particle shape on motion and mixing in this device. Corn seed is used as a model material and the effect of its shape on motion is analysed by considering two approaches: (1) manipulation of rolling friction to account for shape as it is commonly used in the field; (2) approximation of the actual shape by a number of overlapping spheres of various sizes. The geometry of corn seeds is captured using X-ray microtomography and then the ASG2013 software (Cogency, South Africa) is used to generate and optimise the arrangement of the overlapping spheres. A comparison is made of the predicted tangential and radial velocity distributions of the particles from DEM and those measured experimentally. It is concluded that for rapid shearing systems with short collisional contacts a small number of clumped spheres suffice to provide a reasonable agreement with experimental results. Equally well, manipulating the rolling friction coefficient can provide results that match experiments but its most suitable value is unknown a priori, hence the approach is empirical rather than predictive.

1. Introduction

In industries such as agricultural, food, detergent and pharmaceutical manufacturing, granule mixing and coating are common processes. The quality of the finished product is strongly influenced by the rate of mixing and quality of coverage, which themselves depend on the spraying and spreading processes. Hence it is important to understand the effect of each process parameter on the final product quality and to optimise them. To do so, the particle kinematic behaviour (flow field, mixing pattern, etc.) needs to be analysed. Discrete Element Method (DEM) [1] provides a robust way of simulating particulate systems [2–4]. Spherical particles are most commonly used due to the simplicity of contact detection and mechanics, where contact can be detected if the distance between two particles become less than the sum of their radii. This results in efficient contact detection and faster contact force calculations. There are many other approaches for representing particle shape, such as elliptical [5], polygonal [6], bonded assemblies of polygons [7], spherosimplices [8] and super-quadric particles [9]. Lu et al. [10] have recently provided a comprehensive review on approaches for consideration of non-spherical particles in DEM.

To account for the non-sphericity of particles, Morgan [11] proposed a new method for simulating mechanical interlocking of irregularly shaped particles by restricting particles from rolling. This method showed that the addition of rolling friction would lead to more realistic values of bulk friction compared to free rolling spheres. Ai et al. [12] have classified the rolling resistance models into four categories: directional constant torque, viscous, elastic–plastic spring-dashpot and contact-independent models. Wensrich and Katterfeld [13] reported that consideration of rolling friction alone would not lead to an accurate representation of the particle shape in the case of simulating the angle of repose. They attributed this to the fact that the rolling friction only acted to oppose the rolling motion whereas in reality the non-sphericity of a particle may increase rolling.

Favier et al. [14] implemented a new technique for considering particle shape in DEM, where the particle shape was approximated by a number of overlapping or touching spheres with different sizes (known as clumped spheres), the centres of which were fixed in a position relative to each other. This method approximates the shape of irregular particles by a number of clumped spheres, while maintaining computational efficiency. Theoretically, any particle shape can be modelled, although highly angular particles require a large number of small spheres to approximate their sharp edges, making this method unsuitable [15]. Approximation of shape using this technique produces

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undesired surface roughness for the modelled particles [16]. However, the induced roughness can be controlled by increasing the number of spheres, though this has a negative impact on the computational efficiency.

Wiącek et al. [17] investigated the influence of grain shape and inter-particle friction of peas and beans on the mechanical response of the assemblies in a uniaxial compression test. They showed that the mechanical response of the granules was highly affected by increasing the aspect ratio of the particles; the lateral-to-vertical pressure decreased as the particle aspect ratio was increased. Once the aspect ratio of the particles exceeded 1.6, however, the lateral-to-vertical pressure became relatively invariant. Moreover, the authors reported that the DEM simulations predicted values of the effective elastic modulus of the bed close to those obtained from experiments for spherical particles (i.e. peas) but not in the case of oblong particles (i.e. beans). Hare and Ghadiri [18] investigated the effect of particle shape and roughness of particles on their flowability in a shear box by DEM. The particles were represented by a number of overlapped spheres and the roughness was controlled by the separation of the centres of overlapped spheres from one another. They concluded that an increase in roughness of particles resulted in an increased stress ratio. Gonzalez-Montellano et al. [19] investigated the discharge flow of glass beads and corn seeds from silos using DEM, where the glass beads and corn seeds were simulated using spherical and multiple non-adhesive clumped spheres, respectively. Their predictions for the mean bulk density for the filling phase, discharge time and flow patterns were then compared to the experimental results. The authors reported that due to the shape and difficulty of measuring the friction of irregularly shaped particles, the flow pattern and discharge time in the simulations did not follow those obtained in experiments. Therefore, the value of particle–particle friction coefficient was calibrated using sensitivity analysis based on the approach of Balevicius et al. [20]. More recently, Gonzalez-Montellano et al. [21] investigated the vertical and horizontal distributions of the normal pressure, tangential stresses, mobilised friction and velocity profiles of filling and emptying silos using experiments and DEM. They found a reasonable agreement with experiments. However, the predicted horizontal distribution of normal stress on the wall was greater for the central positions on the wall, as compared to those measured experimentally. The authors suggested hybrid models, similar to the work done by Lu et al. [22], where FEM and DEM were coupled to improve the results.

Recently, there have been studies carried out on the adequacy of the number of clumped spheres needed to represent particle shape in DEM. At single particle level, Song et al. [23] investigated this for tablet-shaped particles, where the shape was represented by 10, 26, 66 and 178 mono-size spheres. They analysed the magnitude of angular velocity of a tablet upon impact onto a stationary tablet. They have reported that for all the cases, no agreement could be found between the simulations and experiments, where the magnitude of the angular velocity was much higher in the simulations. They also reported that increasing the number of clumped spheres increased the magnitude of angular velocity of particles upon impact onto another tablet. They attributed this to the fact that there were more sphere contacts when using a larger number of clumped spheres. It should be noted that these findings may not be applicable to clumped spheres representing a bed of particles, since there are more particle–particle contacts in such a system. Similarly, Price et al. [24] investigated the angular velocity of irregularly shaped particles, represented by clumped spheres, upon impact on to a flat steel plate. They reported that increasing the number of clumped spheres did not influence the angular velocity in the case of densely packed spheres, where no voids were present in the structure of the particle. They attributed this to the fact that in the particle shape that they investigated the particle was compact; hence the centroid of the particle was located close to the centre of the particle. It is noteworthy that their simulated particle shape was not highly irregular and the surfaces were smooth; hence further investigation is required for more complex particle shapes. Moreover, the above work only addressed the effect of particle shape at the single particle level. At the bulk level, Markauskas et al. [25] investigated the adequacy of the number of clumped spheres required for DEM simulations in a particle piling system. In their study, an ellipsoid particle shape was approximated using a number of spheres. They reported that the porosity of the bed initially decreased, but remained relatively constant for assemblies consisting of more than 13 clumped spheres. Moreover, the average coordination number of particles increased with the number of spheres used, but again remained relatively constant for particles consisting of more than 13 spheres. In their work, the simulation results have not been directly compared to experiments; hence it is difficult to assess the accuracy of the predictions. In another work, Kodam et al. [26] investigated the accuracy of shape representation by using clumped spheres and actual cylindrical particle shapes for both single particle and bulk levels. In their work, a cylindrical particle as well as two assemblies of 9 and 54 mono-size clumped spheres was considered. At the single particle level, the particle was impacted onto a flat surface and the angular velocity was analysed. Compared to theoretical results, a poor agreement was found in both cases of clumped spheres (9 and 54 spheres), whereas a relatively good agreement prevailed for the actual cylindrical particle shape. Moreover, they investigated the residence time of the particles in a baffled rotating horizontal drum, where a reasonably good agreement was found for all the particle shapes investigated (both clumped spheres and actual cylinders). Further analysis of the bulk solid fraction of particles in a cylindrical vessel showed that using 54 clumped spheres slightly underpredicted the solid fraction. This could be as a result of artificial introduction of surface roughness and could be minimised by considering poly-size spheres in the individual particle assembly; where smaller spheres are present at the surface of the particle to improve the accuracy of shape representation. Kruggel-Emden et al. [27] also raised concern on the validity of using the clumped sphere method. They reported that at the single particle level at least the method did not reliably simulate the real case. However, they suggested that the bulk behaviour might not face the same shortcomings. Guo et al. [28] investigated the effect of particle aspect ratio and surface geometry on granular shear flow of rod-like particles in three regimes of solid volume fractions (i.e. dilute, intermediate and dense regimes).

Much work has been carried out in the literature on consideration of particle shape in DEM simulations. In most cases, the adequacy of the number of clumped spheres required to reliably simulate the real case is investigated at the single particle level, which may not represent bulk behaviour of particles. In this paper however, we report on our work on the effect of particle shape on particle motion in a rotary batch seed coater, using both spherical particles with the addition of rolling friction, and particles represented by clumped spheres and, comparing the simulation results with those obtained experimentally.

2. Materials and methods

2.1. Experiments

A series of laboratory experiments were conducted using a SATEC ML2000 rotary batch seed coater (0.3 m in diameter and 0.21 m in height) as shown in Fig. 1. For the seed coating, a liquid stream is introduced by a nozzle to a spraying disc, where the liquid is atomised and sprayed onto the surfaces of the seeds. The base rotates to mobilise the seeds, whilst the vertical plates act as baffles, turning the bed over and ensuring adequate mixing of the seeds in order to increase the uniformity of the seed coating. In the work reported here the system was run dry, i.e. no liquid was added during the experiments. The interest here is in the analysis of flow and mixing of corn seeds, which are used as the test material. The seeds are sieved prior to the experiments and only particles in the sieve size range of 7.1–8.0 mm are used. The seed mass loading put in the coater is 1.2 kg. For both simulations and