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Calibration and Validation of a Discrete Element Model of Corn Using Grain Flow Simulation in a Commercial Screw Grain Auger

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Calibration and Validation of a Discrete Element Model of Corn Using Grain Flow Simulation in a Commercial Screw Grain Auger

Abstract
Screw augers are primary grain conveying equipment in the agriculture industry. Quantitative prediction of grain conveyance using screw augers requires better understanding and measurement of bulk particle-particle and particle-rigid-body interactions. Discrete element modeling (DEM) has potential to simulate particle dynamics and flow within a screw auger and thus provide simulation-based guidance for auger design and operating parameters. The objective of this study was to develop a DEM corn model calibration methodology and validation for combine-harvested corn flow in a commercial screw auger. The methodology used a virtual design of experiment (DOE) varying DEM corn parameters and calibration to match grain pile formation expressed in a normalized angle of repose (AOR). DEM corn particle shape was approximated using 1-sphere and clumped spheres (2-sphere, 5-sphere, and 13-sphere) matching the measured physical parameters of equivalent geometrical diameter, 2D axial dimensions, 3D axial dimensions, and detailed CAD-approximated corn dimensions, respectively. For each DEM corn shape approximation, a virtual DOE using Latin square hypercube design with four independent DEM Hertz-Mindlin contact model interaction coefficients was developed. The DEM assembly of particles matching the initial conditions of the AOR test was created in EDEM 2.7. From the quasi-static AOR of corn flow in the AOR tests and EDEM simulations, the mean square error (MSE), a sum of square difference in grain heights in the AOR tests and EDEM simulations, was used as a bulk material dependent response for the calibration process. The DEM 2-sphere corn shape model and the material interaction coefficients showed the minimum MSE (5.31 mm) compared to the 1-sphere, 5-sphere, and 13-sphere models. With the best DEM corn shape model (2-sphere) and DEM model parameters with the minimum MSE, validation of the DEM in predicting corn flow in a commercial screw auger in laboratory tests at two rotational speeds (250 and 450 rpm) was performed and showed good prediction (within 5% relative error) in matching the change in mass flow rate with the change in auger rotational speed.

Keywords
Angle of repose, Corn, Discrete element modeling (DEM), Screw grain auger

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
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Mechanical screw augers are commonly used for bulk grain handling in self-propelled combine harvesters and in post-harvest operations such as grain cart loading and unloading (Srivastava, 2006). Understanding and quantitatively predicting the grain-grain and grain-equipment interactions are essential for the development and validation of grain handling machine systems. The traditional iterative product development cycle, i.e., prototyping and conducting laboratory (Miao et al., 2014) and field verification tests, can be laborious, costly, and time consuming. With large-scale grain handling systems, experimental tests that maintain uniform and repeatable grain responses are very challenging to design and are prone to undesirable introduction of test variability due to changes in grain conditions, such as moisture content and grain quality. Dimensionless grain auger performance equations have been developed (Roberts and Willis, 1962; Srivastava, 2006) but could not provide dynamic grain flow behavior responses. Virtual engineering tools for modeling grain interactions with equipment, such as grain auger systems, have potential to augment simulation-based design of bulk grain handling systems and potentially reduce the effort required for field tests. In their work to experimentally quantify screw auger performance for biomass flow, Miao et al. (2014) noted the need for development of a computational simulation of biomass material flow in grain handling equipment to provide quantitative predictions of auger performance and predict dynamic grain flow. Developing a robust numerical methodology along with experimental testing processes for controlled, reproducible field-harvested grain conditions are important research challenges.

Discrete element modeling (DEM), a computational technique originally developed by Cundall and Strack (1979), has become a potential technique for predicting the dynamic behavior of granular materials in powder processing, mining, geotechnical, and agricultural industries (Owen and Cleary, 2009; Ucgul et al., 2014; Pezo et al., 2015). In agricultural applications, DEM has been used for simulation of tillage-soil interaction (Asaf et al., 2007; Chen et al., 2013; Ucgul et al., 2014) and granular material processing, such as
mixing and milling (Cleary, 2013; Kalala et al., 2005; Kretz et al., 2016).

Many users of DEM have demonstrated the qualitative simulation of granular flow dynamics in machine systems (Cleary, 2010; McBride and Cleary, 2009). Quantitative DEM prediction of bulk granular flow in large agricultural machinery, however, has not yet been achieved. In order to integrate DEM as a robust engineering design tool for bulk grain harvesting and post-harvest machine systems, there are limitations to overcome in the methodology for determining DEM material properties of harvested grain and for validating large-scale industrial system simulations. These limitations are mostly due to the lack of a standard methodology for numerically approximating DEM grain models, simple and robust calibration procedures for applicable DEM micro-mechanical contact models, and quantitative validation of DEM simulation models for dynamic grain handling systems.

As a mesh-free technique, DEM simulation of granular material and geometry is not limited by material and geometry meshing, boundary conditions, and instability due to mesh distortion, which are typical limitations of the continuum and mesh-based finite element analysis (FEA) and computational fluid dynamics (CFD) techniques. The robustness of DEM simulation depends on (1) efficient formulation of the simulation domain (particle size, number of particles and geometry system size; and kinematic motion) for the available computing resources, and (2) DEM shape approximation and methods to generate DEM material micro-mechanical properties.

Several researchers have used different approaches for developing or selecting DEM micro-contact models, defining DEM particles, and generating DEM material properties. To determine DEM material properties, one approach that has been widely used appears to be direct measurement of DEM micro-mechanical properties by measuring representative single grain-grain and grain-wall (geometry) DEM coefficients of restitution, coefficients of friction (sliding and rolling), and elastic modulus parameters (Young’s modulus and Poisson’s ratio). González-Montellano et al. (2012) used individual grain micro-mechanical measurements of corn (maize) and olive particles to generate DEM parameter values for particle density, Young’s modulus, coefficient of restitution, and coefficient of friction. They were unable to measure the coefficient of friction for particle-particle interactions due to the lack of standardized methods for measuring this property and recommended the use of a calibration approach when individual DEM parameters cannot be measured experimentally. Other researchers (Coetzee and Els, 2009a; Coetzee et al., 2010) have conducted virtual experiments to predict bulk grain failure parameters (Mohr-Coulomb cohesion and angle of internal friction) from DEM virtual experiments by changing one DEM micro-parameter while fixing all other DEM parameters and applying trial-and-error until matching the bulk material properties. Coetzee and Els (2009b) conducted direct shear tests to measure grain-grain internal angle of friction and uniaxial compression tests to calibrate DEM friction coefficients and stiffness parameters. In their calibration process for comparison with bulk experiment tests, Coetzee and Els (2009b) used a trial-and-error process to calibrate DEM stiffness parameters and reported a maximum blade force prediction error of 26% from validation of a blade-grain DEM simulation. Later, Coetzee et al. (2010) used uniaxial compression tests and angle of repose tests as improvements to the trial-and-error process during the calibration process; however, their trial-and-error approach lacked interactional effects of DEM properties on bulk behaviors.

DEM shape approximation of granular materials has also been of interest in many studies (Coetzee, 2016; Markauskas et al., 2015; Stuhl and Konietzky, 2011; Wiacek et al., 2012). Currently, methodology that integrates DEM shape approximation into calibration of DEM properties for simulation of grain flow dynamics is limited.

The overarching objective of this study was to integrate simple experimental tests for DEM particle shape approximation and develop a quantitative DEM calibration and validation methodology for simulation of combine-harvested corn grain flow in screw auger systems. The specific objectives were to (1) characterize the physical properties of harvested corn using standard measurement methods and simple bulk material flow tests, (2) develop a DEM corn model approximating the shape of harvested corn and DEM material interaction properties based on simple physical experiments and design of experiment (DOE) calibration, and (3) validate the DEM corn model using a commercial screw grain auger.

**Material and Method**

There are several steps in simulating an application using the DEM technique. These steps include choosing the proper contact model for the application and granular material, approximating the particle shape and size, and determining the input parameters for the contact model. A procedure was developed to assist in determining the input parameters. After choosing the contact model, all input parameters can then be listed. Following the developed procedure, the DEM parameters can then be divided into three categories: parameters to be measured, parameters to be obtained from the literature, and parameters to be calibrated. Calibration of a parameter requires obtaining values of the micro-mechanical properties of the material or the interactions between them. This process consists of using a simple test to measure a bulk behavior response and then trying to predict the bulk response by systematically changing the micro-mechanical DEM parameters. When a parameter value is DEM shape dependent and/or application specific, calibration is required. For the remaining parameters, values may be obtained by direct measurement using standard methods. If parameter values cannot be obtained through measurement, literature sources can be used. Considering the dynamic nature of the screw grain auger application (as a flow application without plastic deformation of the particles) and the non-cohesive behavior of corn grain, the Hertz-Mindlin contact model was chosen for this project.

The Hertz-Mindlin contact model is one of the most commonly used contact models in DEM for simulations of non-cohesive granular behavior. The basic Hertz-Mindlin contact
model is a non-linear spring elastic model without cohesion. A general form of the Hertz-Mindlin model can be explained using normal and tangential spring responses in the normal and tangential contact overlaps between particle-particle and particle-rigid-body interactions (fig. 1). Frictional slip is allowed in the tangential direction using a slider and is limited to a maximum value by Mohr-Coulomb friction behavior. The normal and tangential forces both have damping components in which the damping is related to the coefficient of restitution. The Hertz-Mindlin contact model with rolling friction developed by Tsuji et al. (1992) was used as the contact model for DEM simulation of corn flow in EDEM 2.7 (a commercial DEM code) for the angle of repose test and screw auger system.

The Hertz-Mindlin contact model requires particle size and shape for particle definition; particle density, Poisson’s ratio, and shear modulus for material mechanical properties; contact model parameters including coefficient of restitution, coefficient of static friction, and coefficient of rolling friction for particle-particle interactions; and particle-rigid-body interactions. The particle-particle and particle-rigid-body interaction coefficients were assumed to be shape-dependent and were obtained through calibration. The angle of repose is a well-known bulk behavior property of granular materials, so it was used for calibration of the contact model parameters mentioned earlier. The computer used for the simulations was a Dell with an 8-core Intel Xeon E3-1271 3.6 GHz CPU, NVIDIA Quadra K60 graphic card, and 16 GB of RAM. The operating system was 64-bit Windows 10 Enterprise edition.

**PHYSICAL MEASUREMENTS**

**Corn Physical Properties**

For all physical tests, a sufficient quantity of combine-harvested corn was collected during corn harvesting in fall 2015 at the Iowa State University Agricultural and Agronomy farm in Boone, Iowa. Corn moisture content was measured by the oven-drying method at 105°C for 24 h. Corn kernels (sample size = 30) were randomly selected for measuring the axial dimensions, particle density, and particle mass. Five axial dimensions, including height, large width, large depth, small width, and small depth (fig. 2a), were measured with a digital caliper (resolution = 0.01 mm) to describe the mean corn particle size and shape. A mean corn particle was

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**Figure 1. Schematic of general Hertz-Mindlin contact model.**

**Figure 2. (a) Corn kernel sample and (b) 3D scanned and CAD reconstructed corn kernel.**
3D scanned and reconstructed to generate a CAD corn kernel for DEM shape approximation (fig. 2b).

Particle density (ASTM, 2000) of corn kernels was estimated by immersing a measured mass of corn kernels (sample size = 30) in a graduated cylinder. The displaced water volume in the graduated cylinder was measured to estimate the sampled corn kernel volume. Particle density was then calculated by dividing the total particle mass by the displaced volume. The particle density test was conducted with three replicates. For bulk density, a container with an initial height of 200 mm, length of 240 mm, and width of 120 mm was filled loosely with corn kernels. Using the measured corn-filled dimensions (height, length, and width) and the known corn mass of 3 kg, the bulk density (loose filled) was calculated.

**Angle of Repose (AOR) Test**

For the angle of repose (AOR) test, a container with an extended bottom plate and lift gate was manufactured from acrylic sheet material (fig. 3). The height, length, and width of the container were 200, 240, and 120 mm, respectively. The side wall of the container was overlain with a transparent 5 mm × 5 mm grid for measuring the material height. The container was loosely filled with 3 kg of corn, and the top surface was gently flattened. The gate was lifted vertically at an approximate velocity of 5 m s⁻¹ to allow corn particles to flow out onto the bottom plate. The height of the corn particles across the side walls was measured from the grid to reconstruct the AOR at rest. The AOR test was repeated five times.

**Screw Auger Test**

A commercial auger (Westfield Co., Boone, Iowa) with total auger length of 3270 mm, outer tube (shell) diameter of 100 mm, screw blade diameter of 90 mm, pitch length of 100 mm, and intake length of 206 mm was used for testing corn grain flow in a screw auger. The tests were conducted using two auger rotational speeds (250 and 450 rpm) and an inclination angle of 0° from horizontal. The dimensions of the screw auger are shown in figure 4. In each test, the auger
rotational speed was first set to the target value. While the auger was running at a steady rotational speed, 46 kg of corn was poured into the feed hopper at a rate of approximately 20 kg s\(^{-1}\). While the corn was being conveyed through auger, additional corn was added to the feed hopper to maintain an approximately constant mass flow rate. A non-contact laser tachometer (HHT13, Omega) was used to measure the rotational speed during the test to verify that the auger was conveying the material at the desired speed. A digital scale (mass resolution of 0.2 kg) was placed under the collection bin, and the transient corn mass exiting the auger was measured at 4 Hz sampling rate. Tests with 0° inclination and two rotational speeds were also performed with the corn falling onto a flat steel plate to measure the AOR of the corn pile.

**DEM Calibration Approach**

The corn particles were assumed to be a non-cohesive and frictional material. EDEM 2.7 was used for the spherical DEM particle creation and DEM simulation. The EDEM parameters needed to define DEM corn using the Hertz-Mindlin (no slip) contact model include: (1) the DEM corn particle shape (particle size and combination of primitive sphere elements), (2) material properties (Poisson’s ratio, shear modulus, and particle density), and (3) material interaction properties, including particle-particle coefficient of restitution, particle-particle coefficient of static friction, particle-particle coefficient of rolling friction, particle-rigid-body coefficient of restitution, particle-rigid-body coefficient of static friction, and particle-rigid-body coefficient of rolling friction. For the DEM corn shape approximation, four DEM corn shapes that approximate the axial dimensions and derived shape parameters (i.e., aspect ratio, roundness) were developed and used in the calibration process. The values of Poisson’s ratio and shear modulus for corn and rigid-body were obtained from the literature (Boac et al., 2010). The particle density measured using the water displacement method was used as an initial guess, and the particle density in EDEM was later adjusted so that the bulk density in the AOR test matched the initial bulk density in EDEM.

The coefficient of restitution for particle-particle interaction was measured from the initial vertical height (\(h_{\text{initial}} = 200 \text{ mm}\)) and the maximum rebound height (\(h_{\text{max}}\)) of a single corn kernel on a corn-filled cylinder. According to Zhang and Vu-Quoc (2002), the coefficient of restitution is defined as:

\[
e = \sqrt{\frac{h_{\text{max}}}{h_{\text{initial}}}}\quad (1)
\]

Similarly, for the coefficient of restitution for particle-wall interaction, a corn kernel was dropped onto a steel plate and its rebound height was measured. The DEM interaction parameters (particle-particle coefficient of static friction, particle-particle coefficient of rolling friction, particle-rigid-body coefficient of static friction, and particle-rigid-body coefficient of rolling friction) were calibrated using design of experiment (DOE), statistical sensitivity analysis, and surface response optimization modeling. The four material interaction properties were considered in the calibration process, as we assumed that these parameters strongly influence the grain conveyance dynamics in a screw auger system.

**DEM Particle Shape Approximations**

Four primitive DEM corn shapes were created using one sphere (1-sphere), two clumped spheres (2-sphere), five clumped spheres (5-sphere), and thirteen clumped spheres (13-sphere) (fig. 5). These four corn shapes were selected from several iterations by matching the 3D CAD corn shape (fig. 2) and considering the computational costs of DEM simulation. The 1-sphere DEM corn shape matched the equivalent geometrical diameter of a physical corn particle (sample size =30). For the 2-sphere DEM corn shape, the height and maximum width of a corn particle were matched. The 5-sphere DEM corn shape approximately matched the height, maximum width, and maximum depth of a corn particle, and the 13-sphere DEM corn shape approximately matched the five axial dimensions (height, large width, large depth, small width, and small depth). For the DEM simulations, the particle sizes were fixed because the mean standard deviations of the axial dimensions were less than 1 mm.

**DEM Sensitivity and Optimization Criteria**

The interactional parameters of corn and acrylic, i.e., the coefficients of corn-corn static friction (CC_stat), corn-corn rolling friction (CC_roll), particle-acrylic static friction (CA_stat), and particle-acrylic rolling friction (CA_roll), were obtained with a systematic calibration process. The range of values for each parameter was obtained from Boac et al. (2010), Coetzee and Els (2009a, 2009b), and González-Montellano et al. (2012). Because there was a possibility of choosing an infinite combination of these parameters’ values, the DOE method was used to create 27 different combinations of the parameters’ values. After forming these 27 DOE EDEM input decks, the AOR test was simulated for each DOE combinations. The mean square error (MSE) was calculated as a cost function (eq. 2) to obtain the prediction accuracy of each DOE simulation:

\[
\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} (h_i - h_{\text{exp}})^2
\]

where \(h_i\) is the height of corn in the DEM simulation, \(h_{\text{exp}}\) is the height of corn in the AOR test, and \(N\) is the total number of height sample points.

**DEM Validation Using Screw Auger**

The final DEM model developed in the measurement and calibration steps was used to simulate the screw auger system. Screw augers are commonly used in grain handling systems, with a wide range of applications. Screw augers are also a major component of the grain handling system in combine harvesters. Based on the simulation of particles through the auger, it was observed that the granular particles rotate and slide against each other and against the auger blade at high velocity. The particles also experience collisions and accelerations while passing through the auger. The flow of corn as discharged from the auger was compared qualitatively, and the AOR of corn poured on the floor was compared quantitatively.

The screw auger was horizontal (0° inclination), and the tests were performed at two auger rotational speeds (250 and 450 rpm). For the screw auger tests, the corn-steel interac-
tion properties were estimated from the AOR optimized corn-acrylic values and multiplied by the ratio of the laboratory-measured corn-acrylic and corn-steel coefficients after González-Montellano et al. (2012).

The screw auger geometry and the dynamics of the experimental setup (fig. 4), including the inlet corn flow rate, were modeled in EDEM 2.7. EDEM is a user-friendly software for DEM simulation with an easy-to-follow setup process. The simulation setup was as follows. Two materials (corn and steel) were specified, and input parameters, including physical, mechanical, and interactional properties, were assigned to them. The CAD file of the screw auger system was imported into the software, and a virtual box was added on top of the feed hopper as the particle factory (i.e., to insert particles into the system). A dynamic particle insertion method was used to insert particles at a rate of 20 kg s\(^{-1}\) for the first 2 s, followed by slow and steady insertion of another 20 kg of material. The secondary particle insertion rate varied based on the auger rotational speed. The simulation time step was fixed at 5e-6 s, and the simulation was run for 60 s. Data were exported at 0.5 s intervals. The steady-state mass flow rate measured in the experiment was compared with the DEM-predicted steady-state mass flow rate for validation of the DEM material properties.

RESULTS AND DISCUSSIONS

CORN PHYSICAL PROPERTIES

Descriptive statistics (mean, standard deviation, minimum, and maximum) for corn kernel axial dimensions, mass, and material properties are presented in table 1. The corn particle density values were within the range reported by Boac et al. (2010) and González-Montellano et al. (2012), and the dimensional measurements matched the values obtained by Boac et al. (2010). The corn moisture content ranged from 14.9% to 16.1%, which is in the lower range for Table 1. Descriptive statistics for physical properties of combine-harvested corn samples (sample size = 30).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (mm)</td>
<td>12.57</td>
<td>0.91</td>
<td>11.26</td>
<td>14.54</td>
</tr>
<tr>
<td>Large width (mm)</td>
<td>7.99</td>
<td>0.69</td>
<td>6.83</td>
<td>9.84</td>
</tr>
<tr>
<td>Large depth (mm)</td>
<td>4.89</td>
<td>0.98</td>
<td>3.71</td>
<td>7.26</td>
</tr>
<tr>
<td>Small width (mm)</td>
<td>5.07</td>
<td>0.89</td>
<td>3.45</td>
<td>7.00</td>
</tr>
<tr>
<td>Small depth (mm)</td>
<td>3.23</td>
<td>0.39</td>
<td>2.93</td>
<td>4.04</td>
</tr>
<tr>
<td>Kernel aspect ratios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height/large width</td>
<td>1.59</td>
<td>0.19</td>
<td>1.24</td>
<td>2.00</td>
</tr>
<tr>
<td>Height/large depth</td>
<td>2.67</td>
<td>0.55</td>
<td>1.59</td>
<td>3.55</td>
</tr>
<tr>
<td>Kernel mass (g)</td>
<td>0.35</td>
<td>0.06</td>
<td>0.20</td>
<td>0.47</td>
</tr>
<tr>
<td>Moisture content (% d.b.)</td>
<td>15.2</td>
<td>0.16</td>
<td>14.9</td>
<td>16.1</td>
</tr>
<tr>
<td>Particle density (kg m(^{-3}))</td>
<td>1273</td>
<td>48.14</td>
<td>1178</td>
<td>1363</td>
</tr>
<tr>
<td>Bulk density (kg m(^{-3}))(^[a])</td>
<td>771</td>
<td>20.24</td>
<td>754</td>
<td>801</td>
</tr>
</tbody>
</table>

\(^[a]\) Sample size for the bulk density measurement was five replicates.
typical corn harvested at the Iowa State University Agricultural Engineering and Agronomy Research farm in Boone, Iowa. The coefficient of restitution values were 0.25 for corn-corn, 0.57 for corn-acrylic, and 0.61 for corn-steel, which agree with the measurements reported by Boac et al. (2010) and González-Montellano et al. (2012).

**ANGLE OF REPOSE (AOR) TEST**

The AOR of corn, as estimated from the corn height measured with the 5 mm × 5 mm grid on the test device (fig. 6), showed two profiles: an approximately horizontal section (farthest from the gate) and a pile section. Using the grid, the measured corn height in the pile section was assumed to better represent the quasi-static grain flow. The mean AOR of 20.7° (SD = 0.8°; sample size = 5) from the pile section was slightly lower than the literature-reported range (23.1° to 34.7°) for static bulk angle of repose (Boac et al., 2010).

**SCREW AUGER TEST**

The means and 95% confidence intervals of mass corn flow from the screw auger at 250 and 450 rpm are shown in figures 7 and 8, respectively. The slope of the linear regression was used to estimate the mean mass flow. For the 250 rpm test, the mean mass flow rate in the linear mass flow

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Figure 6. (a) Example of grain surface profile and (b) mean of five replicates for corn profile height versus length in AOR tests.

Figure 7. Steady-state mean mass versus time at 250 rpm and 95% lower and upper confidence intervals (LL_95%CI and UL_95%CI, respectively).
regime (15 to 30 s and $R^2 = 0.99$) was 1.44 kg s$^{-1}$ (SD = 0.02; sample size = 3). The mass flow rate at 450 rpm was 2.42 kg s$^{-1}$ (SD = 0.08). With the increase in auger rotational speed from 250 to 450 rpm, the steady state was observed earlier because the total mass of corn used in both tests was the same, but with a wider spread around the mean, which was due to instability of the auger rotational speed at 450 rpm.

**DEM MODEL CALIBRATION**

Figure 9 shows the MSE values for the 27 AOR simulations in EDEM for each DEM corn shape. The 2-sphere corn shape had the lowest mean MSE and standard deviation (611.4 and 362.1 mm, respectively), and the 1-sphere shape had the highest mean MSE and standard deviation (819.7 and 1951.2 mm, respectively), which showed that better shape estimation can reduce the effect of interactional coefficients on simulation results.

For all EDEM AOR simulations, the model computation used a time step of 5e-6 s, an EDEM grid cell of three times the minimum sphere radius, eight processors, and a sampling rate of 20 s$^{-1}$. The computation time required to complete 5 s simulation of the AOR test in EDEM 2.7 was approximately 30, 110, 200, and 320 min for the 1-sphere, 2-sphere, 5-sphere, and 13-sphere corn shapes, respectively. With a fixed shear modulus, changes in the DEM material interaction parameters did not result in noticeable differences in computation time. The major contributor to the increase in computation time was the number of particles and the particle size of the DEM corn shapes.

The 2-sphere corn shape showed the minimum MSE and lower computation time compared to the 5-sphere and 13-sphere shapes. The 1-sphere shape had the lowest computation time and the highest overall MSE compared to the 2-sphere, 5-sphere, and 13-sphere shapes. Considering the lowest overall MSE and reasonable computation time, the 2-sphere corn shape was used for calibration and DEM screw auger validation. The time ratio of auger simulation to AOR test simulation for the 2-sphere shape was 20:1, with an average simulation time of 110 min for the AOR test.

**SENSITIVITY AND CALIBRATION OF INTERACTIONAL PARAMETERS**

The influence of interaction effects of the particle-particle coefficients (CC_stat and CC_roll) on the MSE of the AOR was statistically significant ($p = 0.0171$). The minimum error in matching the AOR from the AOR tests was observed at low settings of CC_stat (0.1) and CC_roll (0.0). At a high setting of CC_roll, CC_stat increased from 0.1 to 0.55 and resulted in a significant change in MSE (fig. 10). The main factor of particle-wall coefficient of static friction (CA_stat) showed a significant effect ($p < 0.0001$) on the AOR test MSE, but the particle-wall coefficient of rolling friction (CA_roll) was not statistically significant ($p = 0.0633$).

Sensitivity analysis of the interactional coefficients also showed a high interactional effect of particle-particle static friction and rolling friction (CC_stat × CC_roll) with a positive trend ($p = 0.03$). If one of the two parameter values is changed, there is a possibility of changing the other parameter to achieve the same MSE as the initial MSE because the difference in MSE response varies at low or high CC_roll settings.

Table 2 shows the calibrated DEM model input interactional parameters for the corn-corn and corn-acrylic systems. The corn-steel parameter value, initially estimated from the
laboratory-measured ratio of corn-acrylic to corn-steel coefficient of restitution, was used for the screw-auger DEM validation. All other DEM parameters are presented in table 3. The values were obtained from different literature sources, and the tables indicate the range of values presented for each variable in the literature.

DEM VALIDATION USING SCREW AUGER

The steady-state mass flow rate of corn from the screw auger and the shape of the corn pile on a flat steel plate at the auger outlet were used as the two responses for validating the DEM simulation of corn flow in the screw auger in comparison with the experimental results. The DEM-predicted steady-state mass flow rates for auger rotational speeds of 250 and 450 rpm were 1.05 and 1.68 kg s\(^{-1}\), respectively (fig. 11). Compared with the experimental results, the DEM prediction errors were 27% and 29% for 250 and 450 rpm, respectively. The measured steady-state mass flow rates, as shown in figures 7 and 8, were 1.44 kg s\(^{-1}\) for 250 rpm, with a theoretical volumetric capacity of 2.6e-3 m\(^3\) s\(^{-1}\) and volumetric efficiency of 0.71, and 2.42 kg s\(^{-1}\) for 450 rpm, with a theoretical volumetric capacity of 4.7e-3 m\(^3\) s\(^{-1}\) and volumetric efficiency of 0.67. Even though the prediction errors of the DEM steady-state mass flow rate appear relatively high, the DEM simulation was able to predict very well the trend in the steady-state mass flow rate as the auger speed changed from 250 to 450 rpm. With the increase in rotational speed from 250 to 450 rpm, the mass flow rate increased by 65% in the experiment, while the DEM showed an increase of 60% (fig. 12).

In addition to the steady-state mass flow rate, the comparison of corn pile formation on the flat steel plate showed good agreement between DEM and the experimental results. The corn piles resulting from 20 kg of corn discharged from
the screw auger are shown in figures 13a and 13b for the DEM simulation and in figures 13c and 13d for the experiment. The AOR of the pile was estimated using an image processing method in Matlab from video frames captured with a high-speed camera (240 frames per second (fps)) and the EDEM post-processing protractor tool. Figure 14 shows the accumulating mass and AOR of the pile from the experimental test and EDEM simulation for four corn masses (10, 20, 30, and 40 kg) while the auger was continuously discharging corn. The DEM simulation underpredicted the angle with a maximum error of 15.5%. However, as shown in figure 13, the DEM predicted a stable pile formation similar to the image-processed experimental pile.

The underprediction of steady-state mass flow rate by the DEM might have been due to the higher ratio of the particle-rigid-body coefficient of friction to the particle-particle coefficient of friction causing a slower flow rate as the corn overcame higher frictional resistance at the auger walls. On the other hand, the DEM particles, after discharging from the auger, formed a smaller angle, which could be due to the relatively smaller particle-particle coefficient of friction. These contrasting simulation responses of mass flow rate and quasi-static particle pile formation point out the importance of improving the calibration of rolling friction, which was approximately zero for both the corn-corn and corn-steel interactions. In addition to the AOR test, another simple test that could show the influence of corn-corn interaction with minimal influence from the wall and further explain the influence of rolling friction might be helpful in further improving the calibration process for quantitative prediction of grain pile formation.

Other researchers have studied quantitative prediction of
auger systems, but no study so far has performed an independent calibration of an auger application. McBride and Cleary (2009) used a ring shear test to measure the frictional parameters of granular materials and created a DEM model based on the measured values for an elevator (screw auger) application. They improved their model by manipulating the input parameters to get better agreement between the DEM simulation and experimental tests for the elevator application. They were able to accurately match the experimental results with the simulation because they used the final application as the calibration application. Fernandez et al. (2011) used DEM simulation to investigate the effect of different screw blade designs on the flow rate and drawdown of material in the feed hopper. In their study, they first optimized their DEM model for screw auger application to agree with their experimental results and then used several screw blade designs for their evaluation. Similarly, Rozbroj et al. (2015) focused on the effect of wear on the mass flow rate of materials in a vertical screw auger after a year of use and investigated the improvement of a DEM model to better predict the system behavior after wear accrued.

Although it is possible to calibrate a DEM simulation model using the final desired application, as the previously mentioned researchers did, there are several applications, especially large-scale industrial applications, for which directly calibrating the DEM model by changing the input parameter values and repeating the simulation would be extremely time-consuming and computationally expensive. There are other benefits of independent calibration, including lower time consumption and the capability of producing a DEM model for certain materials that have good predictability in a wide range of applications and geometries.

CONCLUSION

A laboratory procedure was developed to characterize harvested corn for a DEM grain model, shape approximation, and calibration methodology. A simple angle of repose (AOR) test device was manufactured and successfully used to develop the DEM calibration methodology that examined the influence of corn shape (1-sphere, 2-sphere, 5-sphere, and 13-sphere) and the interaction effects of DEM parameters of corn-corn and corn-acrylic (coefficients of static and
rolling friction) on AOR. A Latin square hypercube design of experiment (DOE) based calibration of the DEM corn model was successfully implemented to generate 2-sphere corn properties with an MSE of 5.31 mm by comparing the static corn material from the DEM simulation and the experimental AOR tests.

Validation of the calibrated DEM corn model was performed by comparing the steady-state mass flow rate and corn pile formation from a commercial screw auger with the experimental tests. Qualitatively, the DEM simulation showed good agreement in the grain flow compared with video data captured at 240 fps and in predicting the trend in mass flow rate (within 5% error) as the auger rotational speed increased from 250 to 450 rpm. However, the quantitative predictions of mass flow rate and static pile angle after the particles were dynamically discharged from the auger require further understanding of the DEM properties. The underprediction of the DEM 2-sphere corn model (within a range of 15% to 30%) in predicting the two quantitative responses (mass flow rate and static pile angle) indicates the need for further improvement of the DEM calibration process to capture the flow regime of grain flow dynamics inside the fast-rotating screw auger. Future studies using multi-response experimental tests and surface response based techniques are in progress.

REFERENCES


Kretz, D., Callau-Monje, S., Hitschler, M., Hien, A., Raedle, M., &...


