Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Determination of the coefficient of rolling friction of an irregularly shaped maize particle group using physical experiment and simulations

Lijun Wang*, Rui Li, Baoxin Wu, Zhenchao Wu, Zhenjun Ding

College of Engineering, Northeast Agricultural University, Heilongjiang 150030, China

ARTICLE INFO

Article history:
Received 14 December 2016
Received in revised form 30 April 2017
Accepted 18 June 2017
Available online xxx

Keywords:
Coefficient of rolling friction
Irregularly shaped particle
Accumulation
Simulation
Golden-section method
Physical experiment

ABSTRACT

The coefficient of rolling friction is an important physical property of a maize particle. It is difficult to obtain the value of this coefficient because of the irregular shape of maize particles. This paper describes an approach that combines the discrete-element method (DEM) and a physical test to determine the coefficient of rolling friction of irregularly shaped maize particles. A novel test platform was used to obtain the maize particle's coefficient of restitution and the coefficient of static friction. EDEM software (DEM-Solutions, United Kingdom) was used to simulate the accumulation of maize particles on particles and on a zincified plate. The golden-section method was used to determine the range of the maize particle's coefficient of rolling friction. A single-factor test was used to determine the relationship between the maize particle's coefficient of rolling friction and their angle of repose. The results obtained from the EDEM simulation were compared with physical test results to determine the intergranular coefficient of rolling friction and the coefficient of rolling friction between maize particles and the zincified plate. Our study demonstrates that the angle of repose increases linearly with the coefficient of rolling friction of maize particles. The effect of the coefficient of rolling friction on the particle movement is studied. The physical verification test indicates that the obtained rolling friction of the maize particles is accurate. The findings of this paper provide a theoretical basis for maize-processing machine design and a discrete-element study of the motion of maize particles inside such machines.

Introduction

Rolling friction will occur when two bodies roll relatively. The coefficient of rolling friction of particles is the basis for the design and improvement of particle-processing machines, including maize-processing machines, seed-sowing machines, and grain harvesters. The intergranular rolling friction and the rolling friction between the particle and the wall are important in the mechanical behavior of the particle. The influence of particle shape and intergranular friction on a material's behavior under uniaxial compression was investigated. Particles with a higher aspect ratio decrease the bulk density but maintain nearly the same bulk stiffness (Wiącek, Molenda, Horabik, & Ooi, 2012). The single-spout fluidized-bed simulation can be improved significantly when rolling friction is introduced (Goniva, Kloss, Deen, Kuipers, & Pirker, 2012). Rolling friction can reduce the horizontal velocity of pea particles that are discharged from a flat-bottomed bin (Balevičius, Sielamowicz, Mróz, & Kačianauskas, 2012). The effects of certain intergranular coefficients of the rolling friction on the accumulation characteristics of particles were obvious (Han, Jia, Tang, Liu, & Zhang, 2014; Nakashima et al., 2011).

Recently, many studies have been conducted on the coefficient of rolling friction between particles and different planes. The coefficients of rolling friction of five balls on different planes were investigated (Dickson, Fuss, & Wong, 2010). The relationship between rolling friction and the rolling speed of a soft ball on a hard plane has been reported to be non-linear (Yung & Xu, 2003). The selected-shape approximation scheme of polyhedral dices affects the numerical results (Höhner, Wirtz, & Scherer, 2013). The coefficients of rolling resistance (CoRR) of some glass and steel pharmaceutical tablets were measured experimentally (Ketterhagen, Bharadwaj, & Hancock, 2010).

Limited studies exist on the effects of different parameters on the coefficient of rolling friction of particles and limited conclusions

* Corresponding author. Fax: +86 451 55190667.
E-mail address: wanglijun@neau.edu.cn (L. Wang).

http://dx.doi.org/10.1016/j.partic.2017.06.003

have been made by researchers. Myant, Spikes, and Stokes (2010) found that the friction coefficient of lubricated compliant contacts converges towards a constant value at high entrainment speeds. The friction coefficient is also reported to increase linearly with increasing mean contact pressure up to a maximum limit above which the friction coefficient is constant (Xiao, Björklund, & Rosén, 2007).

The coefficient of rolling friction of particles has been studied numerically using different approaches. A general model has been proposed to model problems involving dynamic and pseudo-static regimes (Ai, Chen, Rotter, & Ooi, 2011). The variational coefficient of rolling friction of a rigid ball on a soft surface was determined by converting the spin rate to a translational velocity in discrete-element simulations (Weizman, Fuss, & Doljin, 2013). The implemented boundary-element method was used to predict the rolling friction of a smooth rigid sphere on a standard linear viscoelastic solid that is able to handle real viscoelastic materials with a large number of relaxation times (Carbone & Putignano, 2013). Zheng, Zhu, and Yu (2011) used finite-element analysis to investigate the rolling friction of a viscous particle on a rigid plane and a theoretical rolling friction model has been derived based on the contact mechanics. The rolling friction was described by acoustic modelling based on the Greenwood–Williamson elastic microcontact model (Evseev, Medvedev, Grigoryan, & Ermolin, 1993). The coefficient of rolling friction was estimated for simplified shapes using a simple geometric argument that was based on the eccentricity of the contact (Wensrich & Katterfeld, 2012).

The discrete-element method (DEM) is a valuable tool for investigating the microscopic properties of particles where transient forces and energy dissipation are difficult to obtain by conventional experimental techniques (Moreno-Atanasio, 2012; Zhu, Zhou, Yang, & Yu, 2008). The method has been applied in agricultural research related to seed particles, such as rapeseed (Coetzee & Els, 2009; Wiącek & Molenda, 2011). Moreover, it has been used to investigate a vertical mixer with regard to its dispersive and convective mixing mechanisms (Schmelzle, Leppert, & Nirschl, 2015), and when coupled with computational fluid dynamics, it has been applied to investigate the effect of particle shape on the transportation mechanism in a well drilling (Akhshik, Behzad, & Rajabi, 2016). It was also used to investigate a horizontal rotating tumbler with internal baffles and containing a mixture of two types of particles (Maione, De Richter, Mauviel, & Wild, 2015). The DEM was used to predict the internal load and moment distribution within rod-like particles and to examine the velocity, solid fraction, and particle-orientation fields of non-cohesive, sphero-cylindrical particles agitated in a vertical axis mixer for a range of particle aspect ratios and bed depths (Hua et al., 2013, 2015).

The coefficient of rolling friction of particles is a basic and computationally significant property for simulation. The coefficient of rolling friction of visco-elastic objects increases firstly and then drops as speeds increase according to mathematical models (Chua, Fuss, & Subic, 2010). The coefficient of rolling friction between an instrumented ball and a surface is non-linear (Weizman et al., 2013). DEM simulations were influenced by transient rolling friction- conditions (Balevičius et al., 2012; Kuhn, 2014).

More accurate input parameters in a simulation yield more accurate calculation results. A simple assumption may decrease the accuracy and credibility of the study results. Thus, a comprehensive value of the rolling friction of a particle group with a broad size distribution and different shapes should be outlined properly.

Current studies on the coefficient of rolling friction of maize particles focus primarily on single and regular spherical particles. In maize-particle processing, the shapes of most particles are irregular. The microscopic mechanical properties of a particle system are considered to be non-homogeneity and anisotropy. However, it is difficult to obtain an accurate value of the coefficient of rolling friction for non-spherical particles by experimental study.

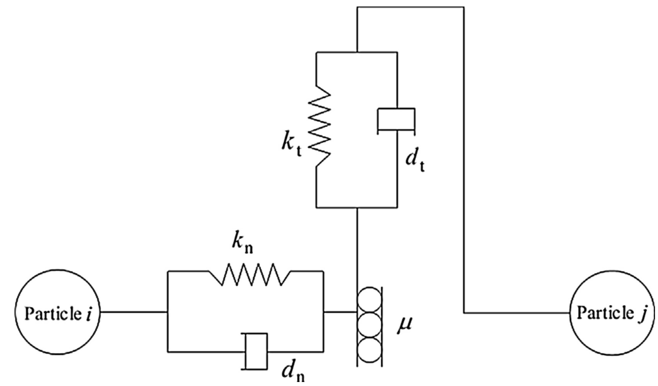

Fig 1. Particle-contact model.

The rolling friction of similar spherical maize particles was studied using a high-speed video camera (Cui et al., 2013). The effects of the coefficient of rolling friction of non-spherical particles on fluidization were investigated experimentally (Liu, Li, Zhao, & Yao, 2008; Liu, Zhang, Wang, & Hong, 2008). However, it is difficult to obtain a precise value of the coefficient of rolling friction of non-spherical particles using only physical experiments. The dynamics of virtual non-spherical particles such as cuboid and ellipsoid particles in fluidized beds are simulated based on DEM (Hilton, Mason, & Cleary, 2010). However, the intergranular rolling friction of irregular particles has rarely been studied.

Two measurement methods exist for DEM contact parameters. One method is physical experiments, and another is a virtual experiment. Physical experiments can be used to obtain accurate coefficients of static friction and restitution of a single maize particle. Because it is difficult for an irregularly shaped particle to roll along the fixed plane, its motion may vary between sliding, rolling, moving up, and moving down during each physical experiment. This paper proposes a method to obtain the coefficient of rolling friction of an irregularly shaped particle based on DEM simulations and a physical test. EDEM software (EDEM 2.6.0, DEM-Solutions, Edinburgh, United Kingdom) is used to simulate the accumulation process of irregularly shaped maize particles. A series of numerical simulations of particle deposition were carried out using the EDEM software (Balevičius et al., 2012). The golden-section method is used to determine the range of the coefficient of rolling friction. A physical experiment that combines the DEM simulation is used to determine the value of the coefficient of rolling friction of a maize particle group. The effect of the intergranular coefficient of rolling friction on the particle accumulation process is analyzed in detail.

Particle-contact model

The Demeiya No. 1 maize variety was studied. The water content of this variety as measured by the drying method (drying oven, DHG-9013A, Shanghai Yiheng Instruments Ltd., China) was 14.23%. Intergranular adhesion can be ignored because of its low water content. Therefore, the contact model of the Hertz–Mindlin (no slip) with relative velocity dependent rolling friction in the EDEM software was selected to simulate the accumulation of maize particles. This model simplifies tangential and normal contact forces into parallel connections of springs and dampers as shown in Fig. 1.