Powder Technology 284 (2015) 187–194

Contents lists available at ScienceDirect

Powder Technology

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

Experimental determination of parameter effects on the coefficient of restitution of differently shaped maize in three-dimensions

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ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 29 May 2015
Accepted 15 June 2015
Available online 23 June 2015

Keywords:
Normal and oblique impact
Particle–wall
Coefficient of restitution
Maize
Experimental tests

ABSTRACT

The coefficient of restitution (COR) is one of the microscopic physical properties of maize that must be specified to use EDEM software to perform numerical simulations to support the design of parts used in maize seeding and harvesting machines. Here, the automatic control platform was designed to measure the COR values of irregular maize. Different parts of maize (the umbilicus and different parts of the maize capsule) are involved in the impact on the horizontal zincified plate. Indeed, some parts' designs are difficult to determine without a variety of tests due to the randomness of the impacting parts. In the present work, the effect of each impacting part of the maize on the COR was investigated. Three types of maize particles were studied, including wedged particles, quadrate particles and round particles impacting on the oblique wall. The velocities of the falling maize particles ranged from 2 to 4 m/s. The mechanical behavior of a particle is stochastic and can be traced by a high-speed camera. The normal and tangential coefficients of restitution were quantified based on the modified kinematic equations presented, and the effects of two factors (the impact and rebound angle of maize) on the COR values were analyzed with impact angles ranging from 30° to 90°. Moreover, the effects of the normal and tangential COR on the total COR in oblique collisions were analyzed. Furthermore, the paper presents a method to determine the COR values of irregular particles colliding with a wall obliquely in three dimensions. The study will be helpful for maize simulation and for the design of machines.

1. Introduction

Most maize kernels are irregular particles. The coefficient of restitution (COR) is one of the key properties of grain particles required in numerical simulation using EDEM software [1–5] for the design of parts in maize seeding and harvesting machines.

The COR can be measured directly [6] or rarely be obtained via calibration due to the dependence on the numerical code used in the calibration process [7–10]. The inter-grain coefficient of restitution (e_p) was obtained based on a double pendulum [11].

Most of the literature presents the coefficient of restitution of spherical and cylindrical particles through experimental tests using various materials, including metal [12], microcrystalline cellulose [13], glass [14] and rubber [15]. Šibanc also determined Young's modulus, the tensile strength and the stiffness of pellets [13].

In addition, both elastic and elastoplastic impacts with an oblique target wall were studied using finite element analysis employing the DYNA3D code [16], and such impacts with a normal wall were studied experimentally [17]. Furthermore, the effect of the number of impacts on the COR was evaluated [18].

There were noticeably fewer studies reported on the determination of COR values of irregularly shaped particles, including rock [19–21] and coke [22], as well as cylindrical polyethylene particles [23], due to the difficulty of the experimental testing. There seems to be a noticeable correlation between the coefficient of restitution and the impact angle [19]. The effect of the average rotational energy pre-impact on the tangential restitution coefficient of rock was investigated [24]. The effect of the average rotational velocity after impact on the normal coefficient of restitution of particles was also investigated [22,24]. The microscopic properties of quadrate maize grains and ellipsoidal olives, including density, Young's modulus of elasticity and the particle–wall normal coefficient of restitution, were tested when particles collided with the horizontal flat surface at different velocities [25]. A purely elastic contact between rock particles accompanied by energy dissipation was studied in [26]. The energy dissipation rates of wet particles were determined for five distinct collision phases [27].

Little data regarding the physical properties of maize could be obtained from the literature. A normal collision with a horizontal surface is the main experimental method. The frictional force is neglected because it is not important in analyzing the normal coefficient of restitution of particles. In the test, to investigate in detail the coefficient of restitution of maize, an oblique impact is used so that tangential and normal movements of the particle can be generated. The effects of

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http://dx.doi.org/10.1016/j.powtec.2015.06.042
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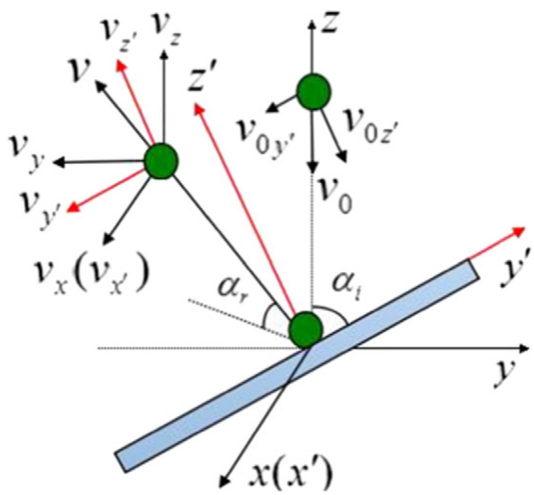

Fig. 1. An oblique impact of a particle in three dimensions.

various factors on the COR of maize were analyzed in this study. Three maize shapes were selected to investigate the COR of maize.

2. Theory

Various definitions for calculating the coefficient of restitution (e) have been proposed based on the velocity and energy. The redefinition of the coefficient of tangential restitution was presented by Antonio Doménech-Carbó, and the *oblique impact* was described by using it [28]. A composite coefficient of restitution (COR) can be determined based on the energy distribution during impact between materially dissimilar bodies [29]. The relationship between the coefficient of restitution and the modal energy was obtained by considering the effects of impact-induced vibration [30].

However, there seems to be no consensus on which equation is more appropriate on the whole [31]. The most commonly used equation to determine COR is the ratio of the impact and rebound velocities (v and v_0) [32] as shown in Eq. (1), which is taken as the basis in this study.

$$e = \frac{v}{v_0} \tag{1}$$

Most maize particles are irregular in shape in general. The direction of motion of an irregular particle is stochastic (Fig. 1) and not in one plane after impact when a particle falls from a height of H. The resistance of air was neglected in this study. The three-dimensional motion of a bead on granular packing was investigated [33]. There have been no investigations of the COR of irregular particles in three dimensions in the related literature.

The velocity of the particle before and after impact can be determined as given by Eqs. (2) and (3) when it falls from a height H. v_x, v_y and v_z, obtained from analyses of images captured by a high-speed video camera, are the velocities of the particle in the x-, y- and z-directions, respectively. Eq. (1) can be further transformed to Eq. (4), where g is 9.8 m s^{-2}.

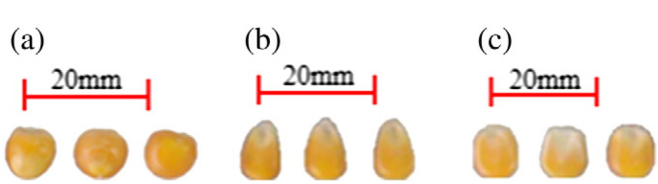

Fig. 2. Different samples of maize: (a) round particles; (b) wedged particles; and (c) quadrate particles.

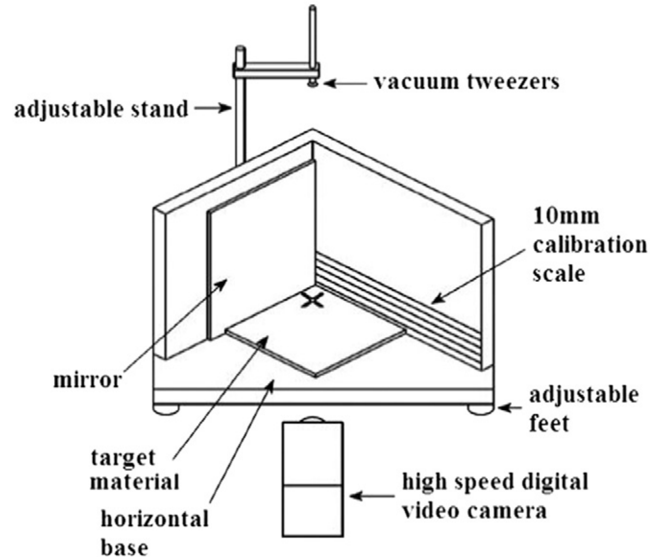

Fig. 3. Coefficient of restitution tester.

$$v_0 = \sqrt{2gH} \tag{2}$$

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2} \tag{3}$$

$$e = \frac{v}{v_0} = \frac{\sqrt{v_x^2 + v_y^2 + v_z^2}}{\sqrt{2gH}} \tag{4}$$

The impact and rebound angles are defined as α_i and α_r, respectively (Fig. 1) [19,22,23]. $v_{oy'}$ and $v_{oz'}$ are the velocities of the particle before impact in the y- and z-directions, respectively [20,34,35]. The coefficient of restitution of the particle can be further divided along its normal and tangential directions into e_n and $e_{t,}$ which can be determined based on two modified equations, as shown in Eqs. (5) and (6). In particular, Eq. (6) was redefined to involve the resultant velocity in two directions along the impact wall after impact to consider all of the motions of the irregular maize, which is an important distinction from what is in the literature.

$$e_n = \frac{|v_{z'}|}{|V_{0z'}|} = \frac{|v_z \sin\ a_i - v_y \cos\ a_i|}{\sqrt{2gH} \sin\ a_i} \tag{5}$$

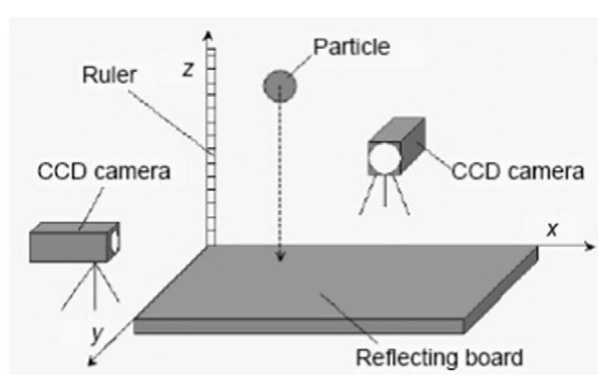

Fig. 4. Layout of the measurement.