ARTICLE IN PRESS
PTEC-12236; No of Pages 7
Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

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

Collision dynamics of wet solids: Rebound and rotation

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ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form 20 December 2016
Accepted 29 December 2016
Available online xxxx

Keywords:
Coefficient of restitution
Rotation
Collision
Impact
Liquid

ABSTRACT

Knowledge about collision dynamics and energy dissipation during particle collision is fundamental for the description of particulate processes. However, such knowledge is still missing for particulate processes that involve liquids. Therefore, in this work rebound behavior of particles impacting normally or obliquely on a wet target plate is investigated experimentally via measuring the coefficient of restitution. In real processes, collisions are mostly associated with particle (initial) rotation, which makes the collision dynamics more complex than just translational energy dissipation. Thus, a focus of this work is on analysis of particle rotation and its influence on normal and tangential coefficient of restitution.

The normal coefficient of restitution was found to be independent of particle initial rotation, but decreases strongly with application of a liquid layer. The tangential coefficient of restitution, on the contrary, is strongly dependent on initial rotation. Initial rotation in direction of rolling leads to an increase of translational tangential velocity, resulting from the conversion of rotational energy to kinetic energy in tangential direction. Accordingly, initial rotational velocity decreases after collision. During collisions without initial rotation, on the contrary, kinetic energy in tangential direction is converted to rotational energy due to friction.

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1. Introduction

Solid processes such as fluidization, pneumatic conveying and mixing are characterized by intense particle-particle and particle-wall interactions. In coating, granulation and agglomeration processes liquids are commonly involved in the form of liquid layers or droplets, resulting in partial or complete wetting of the particle surface. Wet particles behave completely different from dry particles, thus leading to strongly complex bed dynamics e.g. in fluidized beds. Therefore, the knowledge about collision dynamics of wet solids is fundamental for the exact description of such processes. To characterize collision dynamics the coefficient of restitution e is widely used. It is defined as the ratio of rebound velocity v_R to impact velocity v and as such it characterizes the energy dissipated during collision.

$$e = \left|\frac{v_R}{v}\right| = \sqrt{\frac{E_{\mathrm{kin,R}}}{E_{\mathrm{kin}}}} = \sqrt{1 - \frac{E_{\mathrm{diss}}}{E_{\mathrm{kin}}}} \qquad (1)$$

For oblique collisions particle movement can be described by normal and tangential velocities at the particle center and the particle's rotational velocity. Thus the coefficient of restitution can be divided into components. The normal part is defined by the normal velocities:

$$e_n = \left|\frac{v_{n,R}}{v_n}\right| \qquad (2)$$

The tangential coefficient of restitution is often defined at the contact point of the two colliding surfaces, combining translational tangential velocity of the center and rotation. In this work the definition according to Cross [1] is used, because it is consistent with the general definition of the coefficient of restitution, however with opposite sign:

$$e_{t,c} = \frac{v_{t,R} - R \cdot \omega_R}{v_t - R \cdot \omega} \qquad (3)$$

The tangential coefficient at the contact point is below 0 if the particle is dominantly rolling on the surface, while for $e_{t,c} > 0$ the particle slides [1]. However, this definition of the tangential

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http://dx.doi.org/10.1016/j.powtec.2016.12.088
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Please cite this article as: B. Buck et al., Collision dynamics of wet solids: Rebound and rotation, Powder Technology (2017), http://dx.doi.org/10.1016/j.powtec.2016.12.088

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Table 1
Initial rotation in dependence of collision angle.

	Without initial rotation		With initial rotation	
Collision angle (°)	Dry ω_0 (rad/s)	Wet ω_0 (rad/s)	Dry ω_0 (rad/s)	Wet ω_0 (rad/s)
0	0 ± 94	0 ± 97	–	–
10	0 ± 219	0 ± 194	–	–
20	0 ± 103	0 ± 175	698 ± 172	623 ± 188
30	0 ± 163	0 ± 162	1056 ± 179	961 ± 199
40	0 ± 100	0 ± 105	1777 ± 410	1366 ± 196
50	0 ± 310	0 ± 229	2171 ± 384	1777 ± 344
60	0 ± 154	0 ± 161	–	–

coefficient of restitution at the contact point does not allow an analysis of energy conversion between translational tangential movement and rotation. Therefore, alternatively two separate coefficients of restitution for tangential movement as in e.g. [2–5] and for rotation are defined, respectively:

$$e_t = \left| \frac{v_{t,R}}{v_t} \right| \tag{4}$$

$$e_\omega = \left| \frac{\omega_R}{\omega} \right| \tag{5}$$

Dry collisions have been extensively studied, both experimentally and numerically, regarding normal collisions [6,7] and oblique collisions without initial rotation [3,5,8], as well as including initial rotation [8,9]. Also for wet collisions several authors investigated normal collisions e.g. in dependence of collision velocity and properties of the liquid [6,7,10-12]. Müller and Huang [13] and Sutkar et al. [14] proposed analytical models to predict the normal wet coefficient of restitution in dependence of dimensionless parameters. Oblique collisions under wet conditions were studied for example in some recent studies of Ma et al. [4,15].

However, until now a closure equation for the coefficient of restitution during wet collisions including dependencies of all relevant parameters is still under challenge. Moreover, as one of those relevant parameters, the influence of particle initial rotation on the rebound behavior has been mostly neglected. Therefore, this work will focus on these missing issues.

2. Methodology

2.1. Experimental setup

To investigate collisions without initial rotation a single particle is shot by an in-house designed particle accelerator via pressurized air onto a target plate as can be seen in Fig. 1. The impact angle can be changed between 0° and 60° by adjusting the orientation of the particle accelerator. Small initial rotation however could not be prevented (see Table 1). The target plate is covered by a liquid layer of predefined thickness, which is controlled by a confocal sensor (company Micro Epsilon, model confocalDT IFS2405-1). The confocal sensor is positioned on a linear bearing to be able to first measure the layer thickness at the exact area of impact and afterwards move the sensor out of collision zone. The actual collision is captured by two high-speed cameras (company Imaging Solutions, models Y-4 (side camera, capturing movement in x- and y-direction and rotation) and NX-4 (upper camera, capturing movement in x- and z-direction)), allowing for a three-dimensional analysis of collision behavior. A more detailed description can be found in our previous work [16].

To implement initial rotation of the impacting particle, instead of shooting the particle by pressurized air, the particle rolls down a ramp before colliding with the plate. Thereby, the particle obtains initial rotation in direction of rolling (clockwise in Fig. 2). Due to the particle rolling down the ramp initial particle rotation increases with increasing collision angle. The rotation velocity in clockwise direction is in this work defined as positive. The remaining parts of the setup are the same as for collisions without initial rotation.

Table 2
Properties of the Tween 20 solution used in this study at 23 ° C.

Property	Value
Concentration (mg l^{-1})	60
Viscosity η (μPa s)	817.2
Surface tension σ (mN m^{-1})	37.3

Translational velocities in normal and tangential direction as well as rotational velocities are calculated in Matlab (company Mathworks) based on the image series recorded by the two cameras. Impact velocities are velocities of the particle center measured directly before the particle touches the liquid layer and rebound velocities immediately after rupture of the liquid bridge. The impacting particles were marked by several black dots to present rotation of the particles prior to and after impact. Rotational velocities are determined by tracking two dots on the particle surface. Knowing the trajectories of both dots and of the particle center the rotation axis of the particle and the rotational velocity can be calculated. The corresponding coefficients of restitution are determined from those results of velocities. For each parameter configuration at least 30 impacts were measured to calculate the mean values as well as standard deviations shown as error bars in Section 3.

2.2. Materials

$\gamma - Al_2O_3$ spheres (company Sasol) were used to conduct the experiments of particle impact on a glass target plate. The Al_2O_3 particles have a mean diameter of 1.74 mm and a high porosity of approximately 70%, as shown in Fig. 3. The target plate was 80mm × 80mm × 10 mm (W × L × H) in size. The mechanical behavior of Al_2O_3 is elastic-plastic while the glass of the target plate behaves nearly ideal elastic. Therefore, energy dissipation due to the target can be neglected.

As liquid layers an aqueous solution of the surfactant Tween 20 (Polyethylene glycol sorbitan monolaurate, company Sigma Aldrich Co. LLC.) with a concentration of 60 mg l^{-1} were applied to the target with a layer thickness of 100 ± 5 μm. The properties of the investigated liquid are summarized in Table 2. Surface tension was measured by Du-Noüy-method in a K100 Force Tensiometer (company Krüss GmbH) and the viscosity in the RHEOTEST RN 4.1 (company RHEOTEST Medingen GmbH).

3. Results and discussion

The influence of initial rotation of the particle on rebound behavior is investigated by comparing collisions without initial rotation and those including rotation prior to impact. Normal and tangential coefficient of restitution give information about translational movement, whereas rotational velocity as well as rotational coefficient of restitution tell about rotational movement. For all experiments the normal collision velocity is constant at approximately 1 m s^{-1}.

3.1. Normal coefficient of restitution

Fig. 4 shows the relation of the normal coefficient of restitution with collision angle for particles colliding on a dry and a wet wall both with initial rotation and without initial rotation. The normal coefficient of restitution is found independent of collision angle in the investigated range. With the application of a liquid layer, in this case a layer of Tween 20 solution with a thickness of 100 μm, the

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