Particuology 25 (2016) 1–9

Contents lists available at ScienceDirect

Particuology

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

Short communication

Coefficient of restitution for particles impacting on wet surfaces: An improved experimental approach

B. Crüger[a,*], V. Salikov[a], S. Heinrich[a], S. Antonyuk[b], V.S. Sutkar[c], N.G. Deen[c], J.A.M. Kuipers[c]

[a] *Institute of Solids Process Engineering and Particle Technology, Hamburg University of Technology, Denickestrasse 15, 21073 Hamburg, Germany*
[b] *Particle Process Engineering, Department of Mechanical and Process Engineering, University of Kaiserslautern, Gottlieb-Daimler-Strasse, 67663 Kaiserslautern, Germany*
[c] *Multiphase Reactors Group, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 10 April 2015
Accepted 14 April 2015
Available online 30 June 2015

Keywords:
Particle impact
Coefficient of restitution
Liquid layer
Improved experimental setup

ABSTRACT

The coefficient of restitution is widely used to characterize the energy dissipation rate in numerical simulations involving particle collisions. The challenge in measuring the coefficient of restitution is the strong scatter seen in experimental data that results from varying particle properties, i.e. shape and surface roughness, and from imperfections in the experimental technique. To minimize this scattering, a novel experimental setup was developed based on two synchronized high-speed cameras capturing the collision behaviour of a particle in three dimensions. To measure the wet restitution coefficient, which describes particle impact in the presence of a liquid layer in the contact region, additional accuracy can be achieved by measuring the liquid layer thickness by a high-precision optical confocal sensor. The coefficient of restitution was measured for glass particles with two different diameters, at different relative velocities and liquid layer thicknesses, with a focus on small collision velocities and thin liquid layers, using both the improved (three dimensional) and the conventional (two dimensional) approaches to quantify the improvement of the new method's accuracy.

Introduction

Dynamic processes involving solids are widely used in various industries. For instance, in fluidized beds frequently used for drying, granulation, or agglomeration, particles interact with each other and the apparatus walls through a multitude of collisions. Depending on the process, these collisions happen under dry or wet conditions, which significantly influence energy transfer and dissipation during collisions. If the particles are wet beforehand, or are wetted during the process, additional energy losses within the liquid phase and mass transfer of the liquid between the collision partners take place. The energy losses during these collisions are important for proper modelling of particle dynamics and can be described by means of the coefficient of restitution (COR), *e*. The COR is defined as the ratio of the relative velocities of the colliding partners after and prior to impact, v_R and v, respectively. Thus, COR depends on the dissipation of kinetic energy (E_{diss}) during the complete collision (with E_{kin} and $E_{kin,R}$ as being kinetic energy before and after impact):

$$e = \left|\frac{v_R}{v}\right| = \sqrt{\frac{E_{kin,R}}{E_{kin}}} = \sqrt{1 - \frac{E_{diss}}{E_{kin}}}. \tag{1}$$

The COR under dry conditions (e_{dry}) has been subject to extensive experimental and theoretical investigations (e.g. Antonyuk et al., 2010; Hastie, 2013; Kharaz, Gorham, & Salman, 2001). In the dry case, energy dissipation depends mainly on the combination of materials and geometries of the contact partners. However, if liquid layers or droplets are present on the particle or wall surface, as happens in many processes, the COR (e_{wet}) also depends on additional parameters, such as liquid properties, particle dimensions, and strongly on the collision velocity. These dependencies have not yet been fully investigated, especially in the range of small velocities and thin liquid layers, even though these are exactly the conditions present in many processes. For example, in a recent numerical investigation of a spouted bed by Salikov et al. (2015), the reported average inter-particle velocities range from 0.02 to

---

[*] Corresponding author. Tel.: +49 40 42878 3282; fax: +49 40 42878 2678.
E-mail address: britta.crueger@tuhh.de (B. Crüger).

http://dx.doi.org/10.1016/j.partic.2015.04.002

Nomenclature

$d_{50,3}$	mean particle diameter, m
d_P	particle diameter, m
e	coefficient of restitution
e_{dry}	coefficient of restitution for dry collisions
e_{wet}	coefficient of restitution for wet collisions
E_{diss}	energy dissipation, J
E_{kin}	kinetic energy, J
$E_{kin,R}$	kinetic rebound energy, J
h_{conf}	liquid layer thickness measured by means of confocal sensor, m
h_{film}	liquid layer thickness, m
h_{mass}	liquid layer thickness measured by means of liquid mass on target, m
m_L	liquid mass on target, kg
St	Stokes number
St_N	modified Stokes number
v	collision velocity, m/s
v_R	rebound velocity, m/s
Greek symbols	
σ	standard deviation of measurement
μ	mean value of measurement
Acronyms	
COR	coefficient of restitution
CV	coefficient of variation
SD	standard deviation

0.2 m/s in dependence on the apparatus zone. A numerical study by Fries, Antonyuk, Heinrich, Dopfer, and Palzer (2013) compared three different types of fluidized bed granulator configurations, namely a top-spray fluidized bed, a Wurster coater, and a prismatic spouted bed, and reported the particle–particle collision velocity for all three granulator types to be below 0.2 m/s. Additionally, the average particle–wall collision velocities remain below 0.3 m/s for the Wurster coater, below 0.5 m/s in the top-spray granulator, and below 0.7 m/s in the spouted bed. In light of these observations, it seems especially important to investigate the coefficient of restitution for velocities below 1 m/s. However, the majority of research efforts (e.g. work of Antonyuk, Heinrich, Deen, & Kuipers, 2009; Davis, Rager, & Good, 2002; Dopfer et al., 2013; Kharaz et al., 2001; Montaine, Heckel, Kruelle, Schwager, & Pöschel, 2011) have been executed at large collision velocities exceeding 1 m/s. To our knowledge, only Kantak, Galvin, Wildemuth, and Davis (2005) and Gollwitzer, Rehberg, Kruelle, and Huang (2012) have investigated smaller velocities, but there is still extended research that should be done in this field. Furthermore, because the liquid is usually introduced into the fluidized bed by means of a nozzle as fine (μm-sized) droplets, which spread to different degrees on the particle and wall surfaces, it is important to investigate the COR over a range of thin liquid layers.

Additionally, most previous reported measurements display large scatter within the experimental data (Antonyuk et al., 2009; Davis et al., 2002; Kantak et al., 2005). There are several sources for this scatter. On the one hand, energy dissipation is often caused by inelastic deformation or fracture of asperities on contacting surfaces (Montaine et al., 2011). The surface topology varies between particles but also in different contact areas within a single particle. This kind of scatter of the COR is thus natural and specific to a type and batch of particles. On the other hand, there are always errors produced by imperfect measurement techniques.

The objective of this paper is to introduce a novel experimental setup that can reduce those variations resulting from the method. For this aim, we further developed an experimental setup described by Antonyuk et al. (2009), which employs a high-speed camera to record the impact of single particles on a target plate. First, observation of the collision behaviour was extended to a third dimension by adding a second high-speed camera. As a second improvement, a non-stationary high-precision confocal sensor was used to measure the liquid layer thickness exactly at the impact area. Several experiments were conducted to quantify the improvement achieved by the applied changes. Additional measurements were performed with glass spheres of two diameters impacting on a glass plate, for different collision velocities and liquid layer thicknesses, with a focus on small velocities and thin liquid layers.

Methodology

Experimental setup

Fig. 1 schematically shows the experimental setup used in this work. Recording of the particle impacting and rebounding from the target is performed by means of two time-synchronized high-speed cameras (Y-4 and NX-4, Imaging Solutions, Eningen unter Achalm, Germany) with frame rates of 6000–8000 fps. One camera is positioned in front of the target to capture movement of the particle in the x–y plane and the second is positioned above the target to record movement in the x–z plane. Thus, particle movement can be observed in three dimensions, and the results can be verified by comparing the velocities in the x-direction obtained from both cameras. The target is mounted on an anti-vibration table and can be adjusted in the exact x–y plane relative to the first camera by a positioning table. Furthermore, the target can be rotated to obtain a perfectly horizontal position, guaranteeing a uniform liquid layer. The target is bordered on the impact side by a 1 cm wide and approx. 200 μm thick polymer ring to prevent liquid from running off.

The thickness of the liquid layer is measured at the exact impact area by an optical confocal sensor (Confocal DT IFS2405, Micro-Epsilon, Ortenburg, Germany) with an error of less than 1 μm. The sensor is positioned above the impact point by means of a linear bearing and is translated away after the thickness measurement by a stepping motor. Simultaneously the particle, held at a predetermined height above the target by vacuum tweezers, is brought to the former position of the sensor. This is realized by mounting both the sensor and the tweezers' holders on the same linear bearing at a fixed distance from each other and by using a programmable motor for exact positioning. To avoid transfer of vibrations to the target during displacement, the linear bearing is fixed on an exterior frame with no mechanical connection to the anti-vibration table or the target plate. Directly after sensor displacement and particle positioning, the nozzle vacuum is released and the particle drops onto the target. The measurement area is illuminated from the front by two LED lamps (1000 lm) and from the back by a third LED lamp (2700 lm) which is positioned behind an opal glass to achieve diffuse lighting.

After the measurement, the coefficient of restitution is calculated according to Eq. (1) as a ratio of the mean rebound velocity after the liquid bridge has ruptured to the average velocity directly before the impact (Fig. 2). The particle velocities were obtained from image series by a MATLAB script.

Materials

Distilled water at 21 °C with a layer thickness between 100 and 500 μm was used as the liquid layer. The particles were glass beads (Type S, Swarco, Wattens, Austria) with mean diameters