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Experimental study of oblique impact of particles on wet surfaces

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ABSTRACT

Granulation and agglomeration processes are characterized by intense particle–particle and particle–wall contacts. Furthermore, these collisions often happen in the presence of liquid layers due to liquid injection. Therefore the knowledge of micro-mechanics during wet collisions is fundamental for the exact description of such a process. In this work the collision behaviour of dry particles obliquely impacting a target plate covered by liquid layers is characterized by means of restitution coefficients. The coefficient of restitution describes the energy dissipation during an impact and is defined as the ratio of the velocities after and before impact. It is an important parameter for discrete element method (DEM) simulations and depends strongly on the collision parameters (such as collision velocity and angle), particle deformation behaviour (i.e. elastic or plastic) as well as on the properties of the injected liquid (viscosity, layer thickness). To investigate the influence of these parameters on the wet collision behaviour particle–wall impacts were recorded by two synchronized high-speed cameras allowing a three-dimensional analysis of the collision event. The focus of this work is to investigate the influence of liquid layer thickness, viscosity, surface tension and surface roughness on the normal and tangential coefficient of restitution.

1. Introduction

Dynamic processes involving solids are frequently used in various industries, such as chemical, food and pharmaceutical. Especially in granulation and agglomeration processes, for instance in fluidized beds (Salikov et al., 2015; Sutkar et al., 2015) and mixers (Neuwirth et al., 2013), the particles interact mutually or with the apparatus walls through a multitude of collisions. The energy dissipation during these collisions is fundamental for the characterisation and modelling of particle dynamics and is usually described by means of the coefficient of restitution e. The coefficient of restitution is defined as the ratio of the collision velocity after the collision v_R and the velocity prior to the collision v. As such the coefficient of restitution characterizes the dissipation of kinetic energy (E_{diss}) of the particles, with E_{kin} and $E_{kin,R}$ before and after the impact.

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

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These collisions can happen in normal (perpendicular) direction or obliquely as well as between dry or (partially) wet particles, with the last drastically changing the collision behaviour. Wet particles may stick together after collision forming an agglomerate and leading to a coefficient of restitution of zero or they may rebound leading to distribution of the liquid between the particles. The coefficient of restitution under dry conditions was investigated extensively by different authors for the normal as well as the oblique case, e.g. Kantak et al., 2005; Antonyuk et al., 2010; Hastie, 2013; Kharaz et al., 2001; Dong and Moys, 2006; Jain et al., 2012, showing that energy dissipation depends mainly on the combination of the materials and the geometry of the colliding partners, the collision angle and in some respect also on the relative collision velocity. Kantak et al. (2005) observed that for normal impacts the dry coefficient of restitution of Teflon and steel spheres decreases with increasing collision velocity for normal impact velocities below 0.2 m/s, while Antonyuk et al. (2010) found the coefficient of restitution of four different materials to stay constant for velocities between 0.3 and 4.8 m/s. Jain et al. (2012) investigated normal collisions via simulations using a combined volume of fluid–immersed boundary method and were able to reproduce the phenomena experimentally observed by other authors. Wu et al. (2003) investigated normal rebound behaviour for dominantly plastic impacts using finite element methods and found the coefficient of restitution to decrease with increasing collision velocity and to depend on the ratio of Young's modulus to yield stress. For oblique impacts Kharaz et al. (2001) observed the normal coefficient of restitution of aluminium oxide particles to be approximately constant over a range of collision angles between 0° and 85°. The tangential part of the coefficient of restitution however shows a strong dependence on the collision angle with a minimum in the range of 20°. These findings were supported by investigations of Antonyuk et al. (2010), who investigated oblique collisions of four different granules, and Dong and Moys (2006), who investigated oblique impacts of steel balls with and without initial spin. Furthermore, Dong and Moys' experiments indicated a strong dependence of the tangential coefficient of restitution on the initial spin of the particle before impact. The research group of Thornton (Wu et al., 2003, 2009; Thornton, 2009; Thornton et al., 2011, 2013) investigated dry oblique collisions using finite element methods and developed several models to describe normal and tangential coefficient of restitution as well as rotational behaviour for elastic and plastic materials.

If the particles are wetted by liquid layers or droplets on the surface, as happens in many solid processes for instance granulation and agglomeration, the coefficient of restitution depends on additional parameters, such as liquid viscosity, liquid layer thickness, particle size and strongly on the collision velocity. The wet restitution coefficient was investigated for normal collisions by several authors; see for instance (Kantak et al., 2005; Antonyuk et al., 2009; Fu et al., 2004; Dopfer et al., 2013; Gollwitzer et al., 2012). Kantak et al. (2005) showed for steel and Teflon balls impacting on a quartz plate covered by thin layers of silicone oil, that above a critical "sticking" velocity, below which no rebound occurs, the coefficient of restitution increases and ends in a plateau. These results were extended by Antonyuk et al. (2009), who additionally introduced a critical layer thickness and viscosity, which depend on the collision velocity. The coefficient of restitution decreases for increasing layer thickness or viscosity until critical values are reached. But still, the physics of wet collisions and especially the wet oblique collisions are not fully understood.

Several authors also started investigating the influence of surface roughness on dry and wet collisions. Barnocky and Davis (1988) showed for wet collisions that surface roughness has a considerably effect on rebound behaviour if roughness size exceeds a critical elasticity length scale of the solid material. Joseph et al. (2001) additionally demonstrated that surface roughness leads to an increase of scatter of experimental data regarding the coefficient of restitution. Ennis et al. (1991) developed a model based on viscous effects to describe granule consolidation and coalescence. This model predicts if colliding particles rebound or stick to each other after the impact using the dimensionless Stokes number and the surface roughness of the particles as parameters. Liu et al. (2000) extended the model of Ennis et al. including deformation of granules. However, these studies can not fully describe the influence of surface roughness on oblique collisions.

Therefore, this work focuses on the experimental investigation of particles obliquely colliding with a target plate covered by a liquid layer. Measurements were performed for glass spheres impacting a glass plate for different impact angles, liquid layer thicknesses, surface tension and liquid viscosities. Additionally, the influence of surface roughness of the particles and the target plate is analysed.

2. Methodology

2.1. *Experimental setup*

Fig. 1 illustrates the experimental setup used for this work, which is a further development of the setup by Crüger et al. (2015). Instead of the free-fall device the particle impact is initiated by an inhouse-designed particle accelerator that shoots the particle obliquely onto the plate. The impact angle can be adjusted freely and was varied between 0° and 60° by changing the orientation of the accelerator. To perform an impact a single particle is held on the tip of the particle accelerator with the aid of a vacuum pump. It is then accelerated without initial rotation in the direction of the target plate by a pressure surge of pressurised air via a magnetic valve. The collision of the particle and the target is recorded by two synchronized high-speed cameras (company Imaging Solutions models Y-4 and NX-4) with frame rates of 7000 fps. One camera captures the particle impact and rebound in the *x*–*y*-plane being positioned in front of the target, the second camera is positioned above the target recording the movement in *x*- and z-directions. Thereby, a three-dimensional analysis of the collision behaviour can be achieved. To get optimal illumination three LED lamps, two in front of the target and one behind, and a white background are used. The target is made of glass with a size of $W \times L \times H = 80 \times 80 \times 10\,\text{mm}^3$. It is bordered by a 1 cm wide and approximately 200 μm thick polymer ring on the impact side to keep the liquid layer from running off. Furthermore, the target can be rotated by a positioning table to guarantee a perfectly horizontal position and thus a uniform liquid layer. The thickness of the liquid layer is controlled before each impact test by means of an optical confocal sensor (Micro Epsilon confocalDT IFS2405-1) with a measuring error of less than 1 μm.

The normal and tangential components of the coefficient of restitution e_n and e_t are calculated from image series by a Matlab script (company Mathworks) analogous to Eq. (1). Rebound velocities are measured directly after rupture of the

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