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Influence of liquid layers on energy absorption during particle impact

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ABSTRACT

The influence of the thickness of a covering liquid layer and its viscosity as well as the impact velocity on energy loss during the normal impact on a flat steel wall of spherical granules with a liquid layer was studied. Free-fall experiments were performed to obtain the restitution coefficient of elastic–plastic γ-Al_2O_3 granules by impact on the liquid layer, using aqueous solutions of hydroxypropyl methylcellulose with different concentrations for variation of viscosity (1–300 mPa s). In the presence of a liquid layer, increase of liquid viscosity decreases the restitution coefficient and the minimum thickness of the liquid layer at which the granule sticks to the wall. The measured restitution coefficients were compared with experiments performed without liquid layer. In contrast to the dry restitution coefficient, due to viscous losses at lower impact velocity, higher energy dissipation was obtained. A rational explanation for the effects obtained was given by results of numerically solved force and energy balances for a granule impact on a liquid layer on the wall. The model takes into account forces acting on the granule including viscous, surface tension, capillary, contact, drag, buoyancy and gravitational forces. Good agreement between simulations and experiments has been achieved.

1. Introduction

The moisture content in fluidized beds during spray granulation has a great influence on the inter-particle collision properties and hence on the flow behaviour (van Buijtenen, Deen, Heinrich, Antonyuk, & Kuipers, 2009). During this process the most important mechanisms of granule collisional energy loss are the micro processes of coating of the particle surface with a liquid film or droplets and the wetting of the particles. The wetting of particles is accomplished by injection of a liquid binder or a solution, suspension or melt in the granulator. The liquid films and small droplets on the surface could form liquid bridges during the impact and lead to sticking of the particles, i.e. their agglomeration. The images in Fig. 1 taken from particle velocimetry measurements by Börner (2008) show a dramatic change of bed dynamics upon injection of a small amount (5 ml) of water into a bed of 0.51 kg glass particles. During injection the bed height decreases and the particle surface is coated with thin liquid layers or small droplets. On impact the particles stick together due to the development of liquid bridges with high adhesion forces. Thus, the collisional behaviour of glass particles changes from nearly ideal elastic with a restitution coefficient of about $e = 0.97$ to dominantly plastic with adhesion, $e = 0$. Due to the strong liquid bridges, the fluidized bed becomes stable with significantly lower particle velocities and almost no formation of bubbles. The gas evades the major sticky particles to flow through spouting channels, where particles are dried faster and can be separated from the bed. The high air velocity in the spouting channel results in an increased height of the particles by about 20% of the dry packed condition. After drying (Fig. 1c) the bed dynamics returns to the initial behaviour.

Another mechanism of energy dissipation after liquid injection would be the increased moisture content of the porous particles that changes their deformation behaviour from elastic to elastic–plastic or dominantly plastic adhesive (Fu, Adams, Reynolds, Salman, & Hounslow, 2004; Müller, Antonyuk, Tomas, & Heinrich, 2008). Due to liquid content distribution across the apparatus the particles differ in moisture content depending on their distance from the nozzle and their residence time, thus exhibiting different impact behaviour.

The energy loss during particle collisions ($E_{\mathrm{diss,tot}}$) can well be described using the restitution coefficient, which is essentially a material parameter needed for consideration of energy absorption and damping force in discrete numerical simulation of particles (Antonyuk et al., 2009; Kruggel-Emden, Simsek, Rickelt, Wirtz, & Scherer, 2006; Tsuji, Tanaka, & Ishida, 1992). The restitution coefficient is the square root of the ratio of elastic energy

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Nomenclature

d_p	particle diameter (m)
e	restitution coefficient
E_i	energy dissipated by a force i (J)
$E_\mathrm{diss,tot}$	total dissipated energy (J)
E_kin	initial kinetic impact energy (J)
F_b	buoyancy force (N)
F_cap	capillary force of the liquid bridge (N)
F_c	contact force between the particle and the wall (N)
F_D	drag force (N)
$F_\mathrm{l,g}$	gravitational force of the liquid film above the particle (N)
$F_\mathrm{p,g}$	gravitational force of the particle (N)
F_t	surface tension force (N)
F_vis	viscous force (N)
h_br	liquid bridge height (m)
$h_\mathrm{br,max}$	liquid bridge height at the rapture point (m)
h_s	liquid layer height, i.e. thickness (m)
$h_\mathrm{s,st}$	minimum liquid layer height to stick the particle with the wall (m)
m	mass (kg)
R_p	particle radius (m)
R_1	radius of the neck of the liquid bridge (m)
R_2	meridional radius of the liquid bridge (m)
v	velocity (m/s)
x	vertical coordinate of particle centre (m)

Greek letters

α	half of the central angle (°)
γ_la	liquid–air surface tension (N/m)
η	dynamic viscosity of the liquid (Pa s)
θ	contact angle (°)

Subscripts

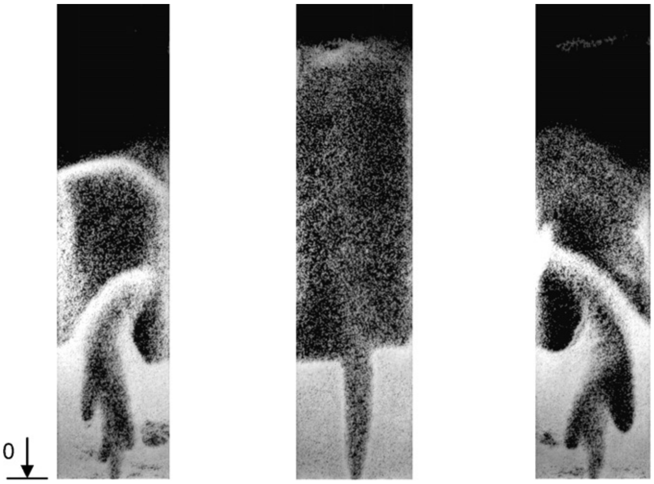
d	damping
el	elastic
n	normal
p	particle
pl	plastic
R	rebound
w	wall

$E_\mathrm{kin,R}$ released during the restitution to the initial kinetic impact energy E_kin:

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

In the case of a fully elastic impact the energy absorbed during compression is fully restored in the rebound phase, and the relative velocities of contact partners before (v) and after ($\mathrm{v_R}$) impact are equal, that is, $e=1$ in Eq. (1). In the case of full absorption of initial kinetic energy due to plastic deformation, adhesion and friction in the contact as well as propagation of the stress waves, the impact bodies are not separated after unloading (restitution), $e=0$. For elastic–plastic behaviour, the restitution coefficient is in the range of $0<e<1$, as exemplified by Goldsmith (1960), Walton and Braun (1986), Labous, Rosato, and Dave (1997), Iveson and Litster (1998), Stronge (2000), Kharaz, Gorham, and Salman (2001), Fu, Cheong, et al. (2004), Fu, Adams, et al. (2004), Antonyuk (2006), and Mangwandi, Cheong, Adams, Hounslow, and Salman (2007).

In the case of colliding particles with liquid films or droplets on their surface, an additional significant contribution to energy absorption is the shear flow of the liquid between particles with formation, extension and rupture of a liquid bridge during the rebound (Ennis, Tardos, & Pfeffer, 1991).



(a) dry fluidized bed (b) during injection of water (c) after drying

Fig. 1. Effect of water injection on fluidized bed dynamics (non-porous glass beads with diameter of 1.5 mm): (a) dry fluidized bed before liquid injection, (b) wetting during injection of 5 ml water, and (c) after complete evaporation of liquid (Börner, 2008).

In this work, we investigate the normal impact of a spherical granule on a wall with a liquid layer, with the objective of investigating the effects of thickness and viscosity of the liquid layer as well as the impact velocity of the granule on energy absorption. Based on measurements and simulations, the influence of these parameters on the critical liquid layer height at which the granule sticks can be obtained. Finally, by comparing the different contributions to the energy loss, the significant influencing parameters can be identified, and subsequent studies would provide a simple efficient model to calculate the effective coefficient of restitution based on liquid layer thickness and viscosity, as well as on particle size and impact velocity.

Relating to the forces acting on a particle, the full period of the impact can be divided into four intervals, as shown in Fig. 2. In the first period, the particle penetrates into the liquid layer of height h_s and squeezes the liquid out of the contact area. The particle–wall contact takes place during the second period, where x_tot is the total displacement of the particle in the loading phase and x_pl is the permanent displacement during unloading. After loss of the contact the particle moves upwards through the liquid and gets out on the liquid layer surface (third period). During the last period a liquid bridge is formed. This bridge will be stretched up to a critical length $h_\mathrm{br,max}$, where its rupture occurs. The restitution coefficient

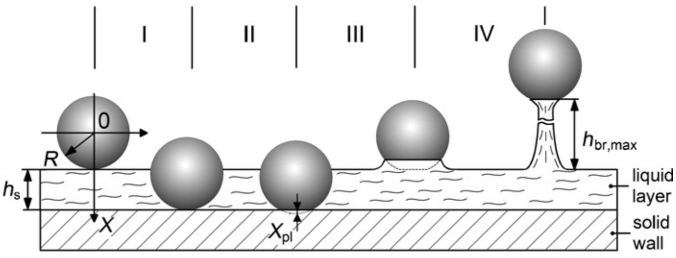


Fig. 2. Schematic representation of impact intervals. I. Penetration of particle into liquid layer: $x{\downarrow}\in[0;\ h_\mathrm{s}]$; II. Contact with the wall (loading–unloading): $x{\downarrow}\in[h_\mathrm{s};\ h_\mathrm{s}+x_\mathrm{tot}]$ and $x{\uparrow}\in[h_\mathrm{s}+x_\mathrm{tot};\ h_\mathrm{s}+x_\mathrm{pl}]$; III. Emergence of particle: $x{\uparrow}\in[h_\mathrm{s};\ 0]$; IV. Formation and rupture of the liquid bridge: $x{\uparrow}\in[0;\ -h_\mathrm{br,max}]$.