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Dynamics of wet particle–wall collisions: Influence of wetting condition

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ABSTRACT

Particulate processes are characterised by intense contacts between particles and particles with the apparatus walls, where often liquid is present on the surfaces in form of droplets or liquid layers, e.g. in granulation and agglomeration processes. However, the influence of the liquid on collision dynamics is still not fully understood. Therefore, the influence of the liquid on wet particle–wall collisions is investigated via the coefficient of restitution (CoR). The CoR characterises the total energy dissipation during a collision and is defined as ratio of rebound velocity to impact velocity. In most literature regarding collision dynamics of wet particles, a target plate is covered by a liquid layer before the collision. However, this approach is often questioned of its similarity to real wet particle collisions. Therefore, during this work the particle was wetted before colliding with a dry or wet plate.

Normal CoR was higher for a wet plate than for a wet particle. The case of a wet–wet collision is comparable to a superposition of collisions where a wet particle or a wet plate was used. Furthermore, during oblique collisions the tangential CoR was found to be smaller for a wet wall compared to a wet particle impacting on a dry wall.

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1. Introduction

In various processes in chemical, pharmaceutical and food industries particulate materials are involved. In such processes the dynamic behaviour of particles during particle–particle and particle–wall collisions dominates the overall behaviour of the system. Furthermore, often liquids are involved, e.g. during granulation, agglomeration or drying, fundamentally changing the dynamic behaviour of the colliding particles. The liquid introduces several additional types of energy dissipation such as viscous, drag and capillary forces (Antonyuk et al., 2009). The overall energy

dissipation during particle collisions is often characterized via the so-called coefficient of restitution (CoR) e , which is defined as ratio of rebound to impact velocity and describes as such the energy dissipation E_{diss} of the system during a collision with the initial kinetic energy E_{kin} .

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

For non-normal collisions it is often defined in normal and tangential directions separately:

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

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Nomenclature

CoR	coefficient of restitution
δ_l	layer thickness [m]
η	viscosity [Pa s]
d_p	particle diameter [m]
E_{diss}	dissipative energy [J]
E_{kin}	kinetic impact energy [J]
e	coefficient of restitution [–]
e_n	normal coefficient of restitution [–]
e_t	tangential coefficient of restitution [–]
m_p	particle mass [kg]
R_p	particle radius [m]
St	Stokes number [–]
v	velocity [m s ^{−1}]
v_n	normal velocity [m s ^{−1}]
v_R	rebound velocity [m s ^{−1}]
v_t	tangential velocity [m s ^{−1}]

$$e_t = \left| \frac{v_{t,R}}{v_t} \right| \quad (3)$$

where v is the collision velocity when the particle is first touching the liquid layer and v_R the rebound velocity after rupture of the liquid bridge, which is formed during rebound. The subscripts n and t indicate normal and tangential directions, respectively. Although knowledge of the dynamic behaviour of wet solids is fundamental to describe particulate processes involving liquids, no full description of such dynamics exists in literature. Many studies already investigated influence of various parameters on rebound of dry particles from walls, covered by liquid layers. Several authors describe a dependence of the coefficient of restitution during normal collisions on Stokes number ($St = \frac{m_p v}{6\pi\eta R_p^2}$), e.g. Barnocky and Davis (1988) and Davis et al. (2002). Ma et al. (2013) however showed that this finding neglects the influence of layer thickness. Other authors prefer studying collision dynamics not via non-dimensional parameters, which always incorporate several influencing parameters, but instead investigate each effect individually. Thereby, for example Kantak et al. (2005), Gollwitzer et al. (2012), Müller et al. (2013), Müller and Huang (2016), and Crüger et al. (2016a) found a characteristic trend of the normal coefficient of restitution with (normal) impact velocity. Additionally, the influence of layer thickness and viscosity were studied for example by Antonyuk et al. (2009), Sutkar et al. (2015), Crüger et al. (2016a,b) as well as Gollwitzer et al. (2012). Generally, a strong decrease of normal coefficient of restitution is found for increasing layer thickness or viscosity. During experiments of oblique collisions of dry particles with wet walls, beside others Kantak and Davis (2004) found out, that the normal coefficient of restitution does not depend on collision angle, if the normal impact velocity is kept constant. Furthermore, the tangential coefficient of restitution as well as angular velocity of the particle after rebound are described to be only marginally influenced by the properties of the liquid layer on the wall in contrast to the previous findings regarding normal coefficients of restitution. Similar results were also reported for different particle materials and with as well as without initial particle rotation in our previous works (Crüger et al., 2016b; Buck et al., 2017). Ma et al. (2015, 2016) describe a slight decrease of tangential coefficient

Fig. 1 – Particle size distribution and SEM images of the glass and γ -Al₂O₃ particles.

of restitution and angular rebound velocity with increasing viscosity and layer thickness.

However, all these previous results were obtained only for a dry particle impacting a wet wall. This is however a strongly simplified system compared to real particle–particle collisions, where either one particle or both particles might be (partially) wet. Furthermore, the wet particles are both able to freely move in space. Thus, the question arises, if the previous findings for wet walls are fully applicable to wet particles. As a first step to approach particle–particle collisions, this work investigates particle–wall collision, where instead of the wall in this case the particle is wet before collision, as well as a collision of a wet particle with a wet wall. Effect of liquid layers, liquid viscosity, surface tension as well as impact velocity and collision angle are compared to previous knowledge about collisions of dry particles with wet walls qualitatively and quantitatively.

2. Methodology

2.1. Materials

The particles used for experiments were glass beads (company Swarco, grinding ball type S) and γ -Al₂O₃ particles (company Sasol), both with a mean particle diameter of 1.74 mm. Both materials behave dominantly elastic during dry collisions in the investigated range of collision velocities ($e_{dry} = \text{const}$). The glass beads feature a high sphericity and nearly no porosity, while the γ -Al₂O₃ also have high sphericity but high porosity of about 70%. All materials, the glass wall, glass particles as well as the γ -Al₂O₃ particles have a surface roughness in the range of a few micrometer, with the γ -Al₂O₃ particles being slightly rougher than the glass spheres and wall. The particles are also highly wettable with dynamic contact angles during rebound of about 15°, measured from collision images. The glass wall features contact angles of about 35°–40° during normal collisions. During oblique collision of a wet particle on a dry wall both a receding contact angle of about 15° on the upper side and an advancing contact angle of about 80° on the lower side of the capillary bridge can be found on the wall. Fig. 1 shows the particle size distribution and SEM-images of both particle types. A glass plate with 80 mm in length and width and 10 mm in thickness was used as the target wall. The influence of three different liquids was investigated: water was used as reference liquid. Using a glycerol–water

Fig. 2 – Schematic representation of the experimental setup for collisions of a dry particle with a wet wall(a), for a collision of a wet particle with a dry wall (b), and an example for particle movement during wetting of the particle and collision with a dry wall (c).

solution with a dynamic viscosity of 3 mPa·s, measured in a RHEOTEST RN 4.1 (company RHEOTEST Medingen GmbH), the influence of varied viscosity was investigated. The influence of surface tension was analysed with the use of an aqueous solution of Tween 20 (Polyethylene glycol sorbitan monolaurate, company Sigma–Aldrich Co. LLC.) with a concentration of 60 mg L⁻¹. This surfactant solution features a surface tension of 37.3 mN m⁻¹ measured with Du–Noüy-method in a K100 Force Tensiometer (company Krüss GmbH). The measured viscosity of this surfactant solution is equal to that of water.

2.2. Experimental setup

Three different configurations of wetting conditions were analysed: dry particles impacting on a wet target plate (case “wet wall”), wet particles impacting on a dry target plate (case “wet particle”) and the case where both particle and wall are wet (“wet-wet”). The setup for the first case with a wet wall was already fully described in our previous works for normal (Crüger et al., 2016a) and oblique collisions (Crüger et al., 2016b). In this case a dry particle is dropped or shot with a particle accelerator driven by pressurized air obliquely onto a horizontal target plate. The target is mounted on a positioning table, which can be angled or covered by a liquid layer, when angled horizontally. Layer thickness on the wall is controlled before each collision by a confocal sensor (Micro Epsilon, model confocalDT IFS2405-1). The collision is captured with 7000 fps by two high-speed cameras (company Imaging Solutions), with one from the front (model Y-4) and

the other from the side (model NX-4), which enables an analysis of the collision dynamics in three dimensions.

For the collision of a wet particle a similar setup is used. In this case the particle drops onto the target plate, which is angled according to the desired collision angles. Before colliding with the plate the particle passes through a ring in which a liquid layer is applied. By passing this liquid layer the particle’s surface is covered by the liquid and afterwards impacts the target plate. Both setups and an example image series for the wet particle’s movement while passing the liquid and impacting the wall are shown in Fig. 2.

For the collision of wet particle and wet wall a combination of both setups is used. The particle is again dropped through the liquid inside the ring before impacting onto the wall, which is covered by a 100 μm thick liquid layer. Since the wall has to be wet before the collisions, it cannot be angled, because otherwise the liquid would run off. However, if instead the particle was shot with pressurized air, as done for collisions of dry particles and wet walls, the pressurized air would destroy the liquid film in the ring, hence the particle would not be wetted before the collision. Therefore, only normal collisions for the wet–wet case were performed.

The thickness of the liquid on the particle’s surface was measured by comparing the diameter measured from the images of at least 10 particles during dry collisions and that of 10 particles during wet collisions for each liquid.

The impact and rebound velocities as well as impact and rebound angles are derived by tracking the particle’s movement via Matlab and averaging over at least 5 recorded images. By additionally recording a scaling object and by knowing the

Fig. 3 – Normal coefficient of restitution for wet particles impacting normally on a dry wall (circles) and for collisions of a dry particle on a wet wall (lines) in dependence of collision velocity for different liquids and varying layer thickness: (a) glass particles and water layer; (b) glass particles with water and Tween 20 layers; (c) glass particles with water and glycerol layers; (d) γ - Al_2O_3 particles and Tween 20 layers.

used frame rate, calculated movement in pixels per image can be converted to velocities in meter per second. From these results normal and tangential coefficients of restitution are calculated.

3. Comparison of “wet wall” and “wet particle” collisions

The coefficient of restitution for normal as well as oblique collisions of a dry particle with a wet wall is compared to those of a wet particle impacting on a dry plate. Therefore, the effect of collision velocity and liquid properties is investigated for exemplary liquids and effects are compared between both wetting conditions. For each collisional configuration at least 10 experiments were performed, the results of which are presented by averaged values and standard deviations. Layer thickness on the particle surface, after falling through the liquid layer inside the ring, varied to some extent with impact velocity, mostly increasing with decreasing impact velocity. The setup of a particle falling through a liquid film did not allow for direct controlling of layer thickness on the particle, but instead layer thickness was a result of a dynamic wetting process. To simplify comparison of different wetting conditions (“wet wall”, “wet particle”), in the diagrams a mean layer thickness averaged over all impact velocities is reported, while the individual layer thickness for each impact velocity is summarized in Tables 1–3.

Table 1 – Average layer thickness of normal collision of wet glass particles with different liquid layers and of wet γ - Al_2O_3 particles. Standard deviation of the dry particles’ diameter, measured in the same way as wet particles, was $\pm 60 \mu\text{m}$ for glass and $\pm 34 \mu\text{m}$ for γ - Al_2O_3 particles.

Glass – water		Glass – Tween 20	
$v \text{ [m s}^{-1}\text{]}$	$\delta_l \text{ [}\mu\text{m}\text{]}$	$v \text{ [m s}^{-1}\text{]}$	$\delta_l \text{ [}\mu\text{m}\text{]}$
0.30 ± 0.03	157 ± 42	0.29 ± 0.02	199 ± 41
0.38 ± 0.03	133 ± 39	0.47 ± 0.02	158 ± 47
0.44 ± 0.03	120 ± 41	0.74 ± 0.02	146 ± 53
0.53 ± 0.05	124 ± 39	0.95 ± 0.01	121 ± 36
0.75 ± 0.02	119 ± 37	1.29 ± 0.02	100 ± 53
1.03 ± 0.03	57 ± 48		
1.20 ± 0.02	72 ± 37		
Glass – glycerol		γ - Al_2O_3 – Tween 20	
$v \text{ [m s}^{-1}\text{]}$	$\delta_l \text{ [}\mu\text{m}\text{]}$	$v \text{ [m s}^{-1}\text{]}$	$\delta_l \text{ [}\mu\text{m}\text{]}$
0.48 ± 0.03	160 ± 39	0.40 ± 0.05	87 ± 20
0.66 ± 0.04	104 ± 44	1.05 ± 0.03	140 ± 41
0.81 ± 0.04	106 ± 37	1.31 ± 0.02	86 ± 23
1.04 ± 0.03	96 ± 40	1.80 ± 0.01	35 ± 28
1.18 ± 0.02	104 ± 38		

3.1. Normal collision

In Fig. 3 the (normal) coefficient of restitution in dependence of the collision velocity during normal collisions is compared for the cases “wet wall” (lines) and “wet particle” (circles). As was already described by several authors (Antonyuk et al., 2009; Kantak et al., 2005; Gollwitzer et al., 2012; Müller and Huang, 2016) as well as in our previous work (Crüger et al., 2016a), for small collision velocities a dry particle sticks to a

Fig. 4 – Comparison of formation and rupture of liquid bridges between the collision of a wet particle and one with a wet wall (collision angle 0° ; layer thickness $\sim 100\ \mu\text{m}$, collision velocity $1\ \text{m s}^{-1}$).

wet wall, leading to a normal coefficient of restitution of zero ($e_n = 0$). After reaching a critical “sticking” velocity the particle is able to rebound (including rupture of the liquid bridge forming during rebound), resulting in a steep increase of the normal coefficient of restitution with increasing collision velocity. The same overall trend can be found in this work both for the case of a dry particle impacting a wet wall, and for a wet particle impacting a dry wall for all investigated liquids and particle materials shown in Fig. 3. Having a closer look at the influence of layer thickness, Fig. 3(a) shows a decrease of the normal coefficient of restitution with increasing layer thickness of water for glass particles impacting on a wet wall. The overall trend with collision velocity is the same for both layer heights. As discussed above, this trend with layer thickness is already well known for collisions of a dry particle and a wet wall (Antonyuk et al., 2009; Gollwitzer et al., 2012; Crüger et al., 2016a,b). Comparing these findings to the results for a wet particle impacting a dry wall, where the average layer thickness was about $110\ \mu\text{m}$, good agreement is found also quantitatively. On average the normal coefficients of restitution for the wet particles are slightly smaller than those for a $100\ \mu\text{m}$ thick layer on the wall, which corresponds to the slightly higher layer thickness on the particles. Only at high collision velocities the normal coefficient of restitution for the “wet particles” is higher than for the “wet wall”, because in those cases the layer thickness on the particle, resulting from falling through the liquid film before impact, are thinner than $100\ \mu\text{m}$ (see Table 1). Consequently, normal collisions of glass particles and thin water layers for “wet wall” experiments and for “wet particle” collisions coincide qualitatively and quantitatively.

Influence of surface tension is considered in Fig. 3(b). During normal “wet wall” collisions of glass particles a decrease of surface tension by nearly 50% shows no influence on the coefficient of restitution, as was also found for oblique collisions in a previous study (Crüger et al., 2016b). Assuming an independence of the normal coefficient of restitution regarding surface tension, again the results for “wet particle” collisions (with $145\ \mu\text{m}$ layer thickness averaged over all collision velocities) fit nicely into the results for the “wet wall”.

Fig. 3(c) addresses influence of liquid viscosity. From literature (Antonyuk et al., 2009; Gollwitzer et al., 2012; Crüger et al., 2016b) it is known that increasing viscosity leads to a decrease of the normal coefficient of restitution due to increasing viscous forces. This can be supported by the findings of this work as well. Both the “wet wall” experiments as well as the “wet particle” experiments show a decrease of the normal coefficient of restitution with increase in viscosity (water to glycerol solution). However, comparing the strength of the viscosity effect, some differences are present. For glass particles and water layers, Fig. 3(a) showed no difference between “wet wall” and “wet particle” collisions. The same results can be found in diagram (c) for water. Comparing now the results for the glycerol solution with higher viscosity, the “wet particle” collisions feature nearly the same and partially even smaller coefficients of restitution than the “wet wall” experiments, although layer thickness is much smaller. Hence, some additional energy dissipation seems to be present for “wet particle” collisions in this case.

This effect might be explained by looking closer at the liquid bridge directly after the collision, compared in Fig. 4. During the rebound of a dry particle from a wet wall, the lower part of the particle carries liquid back up with it. The liquid

Fig. 5 – Normal (a) and tangential (b) coefficient of restitution for wet glass particles impacting obliquely on a dry wall (circles) and for collisions of a dry particle on a wet wall (triangles) in dependence of collision angle.

bridge forms quite uniformly and thins out while the particle travels upwards until the bridge ruptures close to the particle. In contrast, during the collision of a wet particle impacting on a dry plate the liquid evenly distributed over the particle surface gets abruptly accelerated in direction to the plate due to inertia of the liquid and the high momentum resulting from the impact. Thus, when the particle moves upwards while rebounding, the liquid still moves downwards, enlarging the liquid bridge with time and sometimes resulting in asymmetric liquid bridges. This downwards movement of the liquid on the particle leads to additional energy dissipation, which does not appear on a dry particle rebounding from a wet wall. Also during rebound of a wet particle, after some time the liquid bridge starts to decrease in diameter again and ruptures at a certain height. For a wet particle the liquid bridge also tends to rupture close to the plate, while in contrast for a wet wall it ruptures close to the particle.

In Fig. 3(d) the previous results for glass particles are checked for another particle material exemplary by collisions of a $\gamma\text{-Al}_2\text{O}_3$ particle impacting on a glass plate. The collisions are conducted with liquid layers of the Tween 20 solution on particle or wall, because this liquid resulted in the most uniform layers on the $\gamma\text{-Al}_2\text{O}_3$ particles. For collisions of dry particles and a wet wall the known decrease of the normal coefficient of restitution with increasing layer thickness is found. This decrease is stronger for $\gamma\text{-Al}_2\text{O}_3$ than for glass, because of the smaller density of the $\gamma\text{-Al}_2\text{O}_3$ spheres, resulting in smaller inertia of the particle. Hence, the liquid layer has stronger impact on $\gamma\text{-Al}_2\text{O}_3$ particles than on glass. For “wet particle” collisions of $\gamma\text{-Al}_2\text{O}_3$ particles the additional energy dissipation due to inertia of the liquid layer on the particle is distinctly present. Although layer thickness on the particle averaged over all collision velocities is approximately 87 μm , the normal coefficient of restitution is much smaller than that of a corresponding “wet wall” collision. Furthermore, this inertia effect of the liquid is much stronger for $\gamma\text{-Al}_2\text{O}_3$ than found for glass. Comparing the strength of this additional energy dissipation due to liquid inertia for glass and $\gamma\text{-Al}_2\text{O}_3$ particles, the higher effect on $\gamma\text{-Al}_2\text{O}_3$ might be linked to their high porosity. The pores might partially be filled with the surrounding liquid, thus this pore liquid would also be accelerated by the inertia after impact resulting in higher energy dissipation than for the non-porous glass. Additionally, the lower density of $\gamma\text{-Al}_2\text{O}_3$ particles compared to glass leads to a higher effect of energy dissipation due to the liquid in total, as was discussed for “wet wall” collisions of $\gamma\text{-Al}_2\text{O}_3$ particles.

Table 2 – Average layer thickness of oblique collision of wet glass particles. Standard deviation of the dry glass particles’ diameter, measured in the same way as wet particles, was $\pm 60 \mu\text{m}$.

Collision angle [°]	Average layer thickness [μm]
0	120 $\pm$ 36
20	116 $\pm$ 41
30	120 $\pm$ 48
40	73 $\pm$ 39
50	118 $\pm$ 38
60	71 $\pm$ 38

To summarize, a normal collision of wet particles with a dry wall shows generally the same trends as known for collisions of a dry particle with a wet wall. However, the liquid layer on the particle might result in additional energy dissipation due to inertial effects of the mobile liquid.

3.2. Oblique collision

Fig. 5 summarizes the results of normal and tangential coefficients of restitution for collision angles up to 60° from normal. For all collision angles a constant normal collision velocity of 1 ms^{-1} was used. Thus, with increasing collision angle the tangential velocity as well as total collision velocity increase. As liquid layer Tween 20 was used for all oblique collisions. The normal coefficient of restitution for a “wet wall” collision is independent of the collision angle, as was already described for different layer thickness and liquids in our previous work (Crüger et al., 2016b; Buck et al., 2017) as well as in Ma et al. (2013) and Kantak and Davis (2004). Likewise, for collisions of a wet particle on a dry plate the normal coefficient of restitution does not depend on the collision angle. However, the values of normal coefficient of restitution for a collision at 1 ms^{-1} and with a layer thickness of about 100 μm differ between both cases, showing a lower normal coefficient of restitution for a “wet particle” in comparison to a “wet wall”, which was already found for normal collisions of glass particles at high liquid viscosity. This additional inertia effect of the liquid layer on the particle was however not yet shown for glass particles and layers of Tween 20 solution. Fig. 6 compares rebound behavior and liquid bridge formation for oblique “wet particle” and “wet wall” collisions. Generally, rebound dynamics are again similar, however, as mentioned for normal collisions, in the case of a wet particle and dry wall, the liquid bridge does not build up uniformly. Instead the bridge volume

Fig. 6 – Comparison of formation and rupture of liquid bridges between the oblique collision of a wet particle and one with a wet wall (collision angle 40° ; layer thickness $\sim 100 \mu\text{m}$, normal collision velocity 1 m s^{-1}). Consider different direction of gravity due to using an oblique wall during “wet particle” and a horizontal wall during “wet wall” experiments.

Fig. 7 – Normal coefficient of restitution for wet particles impacting normally on a wet wall (circles) and for collisions of a dry particle on a wet wall (lines) in dependence of collision velocity for varying layer thickness.

increases abruptly after about 1 ms, when the liquid layer on the particle is accelerated downwards into the liquid bridge. Furthermore, focusing on the fourth image each the capillary bridge seems to be larger for the “wet particle” compared to the “wet wall” collisions. Capillary forces strongly depend on the volume of the capillary bridge (see for example Mikami et al. (1998)). Thus, the larger capillary bridge volume in the oblique “wet particle” collision might also lead to a smaller normal coefficient of restitution during the “wet particle” collisions compared to the “wet wall” impacts. Additionally, also the bridge’s lifetime is longer for “wet particles” than for a wet wall during oblique collisions. Hence, dissipative forces can act for a longer time leading to more energy being dissipated and thus smaller (normal) coefficients of restitution.

The tangential coefficient of restitution in Fig. 5(b) shows slightly different results for the two wetting conditions as well. Both during collisions with a “wet wall” and a “wet particle” the tangential coefficient of restitution increases with collision angle above 30° . But the tangential coefficient of restitution for the cases with “wet wall” always stays below that of the cases with a wet particle. This difference might result from an influence of the additional liquid on the wet wall compared to the wet particle. Moving tangentially through the

Table 3 – Average layer thickness of wet–wet collisions.

Collision velocity [m s^{-1}]	Average layer thickness [μm]
0.66 ± 0.03	114 ± 49
1.02 ± 0.04	63 ± 47
1.32 ± 0.04	59 ± 50
1.80 ± 0.03	86 ± 43

liquid layer on the plate, the particle has to move aside the liquid, resulting in a drag force acting on the lower part of the particle, which thus introduces additional rotational momentum on the particle. Furthermore, a small wave might be formed due to the shifted liquid amount exerting an additional force. These added forces result in higher energy dissipation for the case with a wet wall than for the wet particle, where a much smaller liquid amount has to be pushed to the sides. Thus, a smaller tangential coefficient of restitution is obtained. Moreover, the gained rotation is not included in the tangential coefficient of restitution and, since it is not measurable quantitatively for the used setup and materials, the rotation cannot be compared between the two cases in detail. However, comparing the images in Fig. 6 a dry particle impacting a wet wall appears to rotate stronger after rebound than a wet particle colliding with a dry wall. At least the capillary bridge is more curved, hinting at higher rotation. Rotation is gained by converting tangential movement into rotation. Hence, higher rotation would correlate with smaller tangential coefficients of restitution, which corresponds to our findings of a smaller tangential coefficient of restitution for “wet wall” collisions compared to “wet particles”. Furthermore, Fig. 6 reveals strongly different contact angles on both sides of the capillary bridge for “wet particle” collisions, featuring a small receding contact angle on the upper (left) side of the bridge and a larger advancing contact angle on the lower (right) side.

4. Comparison of “wet wall” and “wet–wet” collisions

After investigating wet particles colliding with a dry wall, the next question would be, if a collision of a wet particle and a wet wall is a combination of a “wet wall” and a “wet particle” collision. Fig. 7 compares a wet–wet collision with collisions of a dry particle with a wet wall. During the wet–wet col-

lision a 100 μm layer of Tween 20 was applied to the plate. The mean liquid layer thickness on the particles averaged over all wet–wet experiments was 80 μm ranging from about 114 μm at the smallest collision velocity of 0.66 m s^{-1} to 59 μm at 1.32 m s^{-1} . Thus, the sum of the layers on particle and plate is 180 μm on average. The exact layer thickness on the particles for each collision velocity is summarized in Table 3. Comparing the “wet wall” collision with a layer thickness of 200 μm with the wet–wet collision, qualitatively good agreement is found. Quantitatively, the results for wet–wet collisions again are slightly smaller than those of a “wet wall” at the same total layer thickness: the normal coefficient of restitution for wet–wet collisions are mostly smaller than the values for a 200 μm thick liquid layer on a wet wall, although the total liquid layer thickness of the wet–wet collisions is mostly smaller than 200 μm . The results imply that wet–wet collisions might indeed be a superposition of the cases “wet particle” and “wet wall”. Consequently, the effective layer thickness during a wet–wet collision is the sum of the layer on the particle and the layer on the wall. Additionally, the inertia effects of the liquid on the particles surface have to be considered for the effective coefficients of restitution.

5. Conclusion

The influence of wetting conditions on normal and tangential coefficients of restitution for wet particle–wall collisions was investigated by comparing collisions of a wet particle with a dry wall and collisions of a wet particle and a wet wall to the often investigated case of a dry particle impacting a wet wall. Effect of varying normal impact velocity, impact angle and liquid properties were compared. The results can be summarized as follows:

1. The overall trends for the normal coefficient of restitution in dependence of the investigated parameters known for collisions of a dry particle and a wet wall are transferable to the two other wetting conditions of a wet particle and a wet–wet collision: a characteristic increasing trend with collisions velocity is found. With increasing layer thickness and viscosity the normal coefficient of restitution decreases, while it has no dependence on surface tension.
2. However, the values of CoR in cases of wetted particles are often smaller than those in case of dry particles. This decrease of CoR can be explained by the phenomenon that the liquid attached to the particle still moves downwards after impact, while the particle rebounds and moves upwards, which results in additional energy dissipation.
3. During oblique collisions, the normal coefficient of restitution is independent of impact angle, if normal impact velocity is kept constant, while the tangential coefficient of restitution increases with impact angle for angles between 30° and 60°.
4. The tangential coefficient of restitution is slightly higher in cases of a wetted particle than in cases of a wet wall. Supposedly, the difference results from slightly higher energy dissipation in the widespread liquid on the plate than in the smaller amount of liquid on the wet particle. Additionally, different rotation after rebound might be a reason for this result.
5. Wet–wet collisions seem to be a superposition of collisions in cases of when either the particle or the plate is wetted.

To verify, if the results of the simplified system of particle–wall collisions can be transferred to particle–particle contacts, ultimately actual wet particle–particle collisions have to be conducted. Nevertheless, this work already showed some discrepancies if instead of the usually used setup of a dry particle and a wall covered by a liquid layer, the particles are wet before the collision. As next step the setup for wetting of the particles could be improved to be able to apply a defined layer thickness on the particles. This would also allow investigating influence of varying particle size on collisions with wet particles, as particle size is often reported to have a strong influence on collision dynamics of dry particles impacting wet walls (Gollwitzer et al., 2012; Müller and Huang, 2016). Afterwards, particle–particle collisions need to be addressed.

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