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Normal and oblique impacts between smooth spheres and liquid layers: Liquid bridge and restitution coefficient

Jiliang Ma, Daoyin Liu *, Xiaoping Chen

Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, PR China

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ABSTRACT

Detailed understanding of individual collision mechanics of particles in the presence of liquid is crucial for modeling wet particle flows that are omnipresent in nature and various industries. Our early work (Ma et al., 2013) preliminarily characterized the oblique impacts between rough-surface sphere and liquid layers with wide-ranging impact parameters by means of restitution coefficients. The current paper deepens the early work by performing both normal and oblique impacts between smooth-surface collision bodies, focusing on the collision details such as liquid bridge configuration, liquid layer morphology as well as the restitution coefficients with the aid of improved experimental setup. Different from static liquid bridge or the dynamic bridge with constant liquid volume, the formation and development of impact-induced liquid bridge is greatly influenced by the inertia of surrounding liquid that could be represented by liquid Reynolds number. Moreover, liquid inertia is also found to affect the total kinetic energy reduction of spheres through changing the layer morphology, thus having to be considered during theoretical modeling. Liquid bridge force contributes a lot to the energy reduction of rebounding sphere in the normal direction, while has little effects in the tangential direction. For the oblique impacts of smooth spheres with thin liquid layers, no matter how viscous the liquid is, the tangential restitution coefficients are always maintained at higher values than dry impact for the lubrication effect exerted by liquid. The effect gradually weakens as the layer thickness increases. The lubrication effect is not observed for rough-surface impacts owing to the additional energy reduction caused by the physical interaction between surface asperities. Due to the significant role of layer thickness in the energy dissipation process, the liquid drag force arising during the impacts with considerable thickness has to be considered in the development of theoretical models for restitution coefficients.

1. Introduction

It is common in a variety of industrial processes that a small amount of liquid is added into a particulate system, e.g., particle synthesis and surface modification, pharmacy, and food processing. The liquid induces cohesion between particles by coating the particles as liquid layers [1,2], thus leading to different flow behaviors from dry particles in e.g., hopper [3], rotating mixer [4,5], and fluidized bed [6–10]. Particle-particle and particle-wall collisions play key roles in such multi-phase flows. Therefore, a detailed understanding of the mechanics of individual collisions with liquid is a feasible path to reveal the mechanics of these flows [11].

Davis et al. [12] provided the first step in studying the collisions in the presence of liquid by proposing a dimensionless criterion, the Stokes number, to decide whether the sphere would rebound subsequent to normal impact ($St_d = mV_i/6\pi\mu a^2$, where m is the sphere mass; V_i is the impact velocity, μ is the liquid viscosity, and a is the sphere radius). With the aid of an impact setup, numerous investigations were performed to study the energy dissipation arising in the normal collisions. The researchers determined the lowest impulse [13], drop height [14] and impact velocity [15] required for a sphere to separate from the liquid layer. Kantak et al. [16] extended the investigation to an oblique impact and proposed equation correlation to predict the tangential restitution coefficient. The Hrenya group from the University of Colorado investigated three-particle normal collisions with liquid coating and observed more outcomes as compared with particle-plate collisions [17–19].

Most of the above experimental work was guided by the elastohydrodynamic theory [12], where $h << a$ is the prime condition (h is the liquid layer thickness and a is the sphere radius). Regarding the importance of liquid layer thickness, Antonyuk et al. [20] and Gollwitzer et al. [21] found that the restitution coefficient decreases with increasing layer thickness. Sutkar et al. [22] developed a new model for the estimation of the restitution coefficient by grouping the liquid layer thickness into well-known dimensionless numbers such as the liquid Reynolds number and Weber number. Recently, Crüger et al. [23] demonstrated the importance of liquid layer thickness in energy dissipation based on a novel experimental setup. In the previous

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* Corresponding author.
E-mail addresses: topony@163.com (J. Ma), dyliu@seu.edu.cn (D. Liu), xpchen@seu.edu.cn (X. Chen).

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Notation

Roman symbols

a	sphere radius (m)
A_D	characteristic area for drag force (m^2)
A_s	characteristic area for viscous stress (m^2)
C_D	drag coefficient
d	sphere diameter (m)
d_b	base diameter of liquid bridge (m)
$d_{b,max}$	maximum base diameter of liquid bridge (m)
d_{pe}	equivalent diameter of the immersed part of the sphere (m)
e	restitution coefficient (−)
e_n	normal restitution coefficient (−)
$e_{n\text{-}dry}$	normal restitution coefficient of dry impact (−)
e_t	tangential restitution coefficient (−)
$e_{t\text{-}dry}$	tangential restitution coefficient of dry impact (−)
E_g	kinetic energy dissipated solely by gravity (J)
E_i	Young's modulus of collision body (GPa)
E_{in}	initial kinetic energy before the impact (J)
E_l	kinetic energy dissipated by the liquid bridge force (J)
E_r	initial kinetic energy at the bridge formation (J)
E_{rot}	rotational energy (J)
E_w	kinetic energy dissipated by liquid bridge force and gravity (J)
F_D	drag force (N)
f_s	viscous stress (kg/ms^2)
h	liquid layer thickness (m)
$h\sim$	dimensionless length scale (−)
m	sphere mass (kg)
r_h	radius of deformed surface during the impact (m)
R	proportion of kinetic energy dissipated by liquid bridge force (−)
R_n	dissipative ratio by liquid bridge force in the normal direction (−)
R_t	dissipative ratio by liquid bridge force in the tangential direction (−)
R_g	dissipative ratio by gravity (−)
Re_l	liquid Reynolds number (−)
Re_p	particle Reynolds number (−)
St_d	Stokes number (−)
St_{dc}	critical Stokes number (−)
St_m	modified Stokes number (−)
St_{mt}	modified Stokes number in the tangential direction (−)
t	time (ms)
t_s	time of action of viscous stress (ms)
V_i	initial impact velocity (m/s)
V_{id}	sphere velocity at $x = x_1$ (m/s)
V_{ie}	sphere velocity at $x = 0.01a$ (m/s)
V_{ni}	normal impact velocity (m/s)
V_{ti}	tangential impact velocity (m/s)
V_{nr}	normal rebound velocity at the bridge rupture (m/s)
V_{tr}	tangential rebound velocity at the bridge rupture (m/s)
V_{n1}	sphere velocity at bridge formation for normal impact (m/s)
V_{n2}	sphere velocity at maximum bridge length for normal impact (m/s)
V_{n1}'	sphere velocity at the same position to V_{n1} under dry impact (m/s)
V_{n2}'	sphere velocity at the same position to V_{n2} under dry impact (m/s)
V_{t1}	tangential velocity of sphere at bridge formation (m/s)
V_{t2}	tangential velocity of sphere at maximum length point (m/s)
x	distance from the sphere tip to the plate surface (m)
x_1	elasticity length scale for deformation (m)
x_b	mean size of bumps (m)
ΔE_{acc}	kinetic energy change of the fluid before and after the impact (J)
ΔE_{visc}	kinetic energy dissipated by the viscous damping force (J)
ΔE_b	kinetic energy dissipated by the surface energy change of the fluid (J)

Greek symbols

μ	liquid viscosity (mPa·s)
ε	elasticity parameter (−)
ν_i	Passion ratio of the collision body (−)
ρ_l	liquid density (kg/m^3)
ρ_p	sphere density (kg/m^3)
$\rho\sim$	dimensionless density (−)
φ_i	impact angel (°)

Acronyms

HPMC	hydroxypropyl methylcellulose

work, we also reported close relations between liquid layer thickness and restitution coefficients for oblique impact, and proposed a modified Stokes number $St_m = mV_i/\mu dh$ (d is the sphere diameter) to incorporate the effects of the layer thickness [24].

Although restitution coefficients can well describe the total energy loss during particle impact, it cannot distinguish the information from different damping sources, especially for the liquid layers with considerable thicknesses. Therefore, the theoretical modeling of restitution coefficient requires deep understanding of collision details that might contribute to energy dissipation. Reviewing the existing studies, in our opinion, there are several impact features still unclear, but crucial for modeling process:

1.1. Dynamic liquid bridge

During the penetration of spheres with lyophilic surface, the liquid spreads over the sphere surface with a larger interface tension which stretches the liquid out of layer surface under the effect of liquid surface tension, forming liquid bridge as the sphere rebounds [25]. The liquid bridge becomes thinner with rebounding and ruptures when the sphere kinetic energy is larger than the bridge rupture energy [26]. The liquid bridge force, arising with the appearance of the bridge, contributes to the energy dissipation of spheres, thus reducing the sphere velocity [20,24]. The force consists of static and dynamic components, both depending on the bridge geometry and liquid properties [27–29]. Till now, majority of studies about liquid bridge focus on the static cases [30–32] or the dynamic cases with constant bridge volume [26,33]. Few studies concerns the dynamic formation process of liquid bridge subsequent to impact on liquid layers, although the flow of surrounding liquid has been found to greatly influence the liquid bridge geometry as well as the corresponding liquid bridge force [34].

1.2. Liquid layer morphology

It has been widely accepted that part of the kinetic energy of impacting sphere would transfer to the liquid, behaving as liquid flows [21]. On one hand, the liquid flows influence the liquid bridge force through changing the geometry of liquid bridge as introduced previously; on the other hand, they would also affect the energy dissipation process by changing the liquid layer morphology which controls the resistance acting on the sphere during penetration and rebound. This feature is more obvious for the layers with considerable thickness, but seldom reported so far.