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Oblique impact of droplets on microstructured superhydrophobic surfaces

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ABSTRACT

This paper studies the oblique impact of droplets on microstructured superhydrophobic surfaces with the lattice Boltzmann method. Three-dimensional simulations are performed based on the pseudopotential multiphase model, with the Carnahan-Starling equation of state and the multiple-relaxation-time collision operator adopted to overcome the numerical instability problems at high liquid/gas density ratio and low fluid viscosity. The droplet impact dynamics is simulated in a wide range of normal *Weber* numbers (0–30), *Ohnesorge* numbers (0.002–3), and impact angles (15°–90°), with particular interest in understanding different types of bouncing behavior and their effects on the contact time. The results show that, among the four possible types of bouncing identified in the simulation, including conventional retracting bouncing, incomplete-retracting bouncing, impaled retracting bouncing, and tumbling bouncing, incomplete-retracting bouncing and tumbling bouncing have less contact time and could be facilitated by increasing the impact obliqueness. The increase in the normal *Weber* number leads to a transition from conventional retracting bouncing, to incomplete-retracting bouncing, and then to impaled retracting bouncing. The contact time shows a non-monotonic trend of "decrease"-"increase"-"decrease" with enlarged *Ohnesorge* number, and the sheer drop in the contact time at high *Ohnesorge* numbers is due to the occurrence of tumbling bouncing.

1. Introduction

The impact of liquid droplets on solid surfaces is of great interest due to its practical relevance to spray cooling [1], inkjet printing [2], anti-icing [3], engine combustion [4], etc. It has been found that various impact outcomes including deposition, rebound, receding break up, spread, prompt splashing, and corona splashing [5–10] could occur, depending on the joint effects of the droplet properties (*e.g.* density, viscosity, surface tension, and diameter), the impact parameters (*e.g.* impact velocity, and impact angle), as well as the surface characteristics (*e.g.* chemical and physical properties, surface roughness, and temperature). Recently, by recognizing the critical role of wettability on the impact process, superhydrophobic surfaces with microstructures, whose contact angles generally exceed 150° and contact-angle hysteresis are within 10°, have attracted particular attention [11] due to its prominent non-wetting properties and great potential in oil-repellency [12], anti-icing [13], self-cleaning [14], and anti-corrosion [15].

When a droplet impacts on a superhydrophobic surface, it tends to rebound, and the contact time from the initial touch to the final separation is critical to characterize the non-wetting performance of the superhydrophobic surface. For droplets impacting on the horizontal superhydrophobic surfaces, Richard et al. [16] found that the contact time is independent of the impact velocity, and the contact time was scaled as $\tau = \sqrt{\rho_l D_0^3/8\sigma}$. Through introducing macro-textures on superhydrophobic surfaces, non-axisymmetric droplet retraction could be induced, resulting in a significant reduction of the contact time up to 53% [17–19]. Such rapid bouncing by symmetry breaking could be also realized on curved surfaces [20]. For droplets impacting on the superhydrophobic surfaces with pillar arrays, Liu et al. [21] experimentally identified a new type of bouncing named "pancake bouncing", in which the droplet rebounds before lateral retraction, reducing the contact time by 80% compared with the conventional retracting bouncing. For "pancake bouncing" to occur, the criteria of appropriate retraction time and sufficient kinetic energy must be satisfied simultaneously [22]. Pillar structure with a large apex angle [23] was thereafter found to promote "pancake bouncing" and reduce the contact time. Song et al. [24] further studied the

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Nomenclature

A	droplet projection area in the horizontal plane
A_0	initial droplet projection area in the horizontal plane
b	distance between the pillars
D	spreading diameter of the droplet
D_0	initial diameter of the droplet
E_S	surface energy of the droplet
$E_{K\text{-}N}$	normal kinetic energy of the droplet
$E_{T\text{-}initial}$	initial total energy of the droplet
$E_{S\text{-}initial}$	initial surface energy of the droplet
f	discrete particle distribution function
G	fluid-fluid interaction strength
G_s	fluid-solid interaction strength
h	height of the pillar
H	thickness of the liquid film
H_{rim}	thickness of the rim
p	pressure
s	relaxation parameter in the collision process
s_w	binary function to identify solid/fluid
T	temperature
t	time
t_{ocs}	oscillation time of the droplet, $t_{osc} = \sqrt{\rho_l D_0^3/8\sigma}$
t^*	normalized time, $t^* = t/t_{osc}$
$t^*_{contact}$	normalized contact time, $t^*_{contact} = t_{contact}/t_{osc}$
w	width of the pillar

Vectors/Matrix

$\boldsymbol{e}_i$	discrete velocities
$\boldsymbol{F}$	external force
$\boldsymbol{F}_{int}$	fluid–fluid interaction force
$\boldsymbol{F}_s$	fluid–solid interaction force
$\mathbf{M}$	orthogonal transformation matrix
$\mathbf{m}$	particle distribution function in moment space
$\mathbf{S}$	diagonal collision matrix
$\boldsymbol{u}$	equilibrium velocity
$\boldsymbol{U}$	initial velocity of the droplet
$\boldsymbol{V}$	fluid velocity
$\boldsymbol{x}$	position

Greek letters

ρ	density
σ	surface tension coefficient
μ	dynamic viscosity
ϕ	interaction potential
α	impact angle
ζ	bulk viscosity
v	kinematic viscosity
θ_{app}	apparent contact angle
β	weight coefficient in the force term

Superscripts/Subscripts

$*$	dimensionless number
c	critical parameter
eq	equilibrium
g	gas phase
i	ith direction
l	liquid phase
N	normal direction

Nondimensional parameters

Oh	*Ohnesorge* number, $Oh = \mu_l/\sqrt{\rho_l \sigma D_0}$
We	*Weber* number, $We = \rho_l U^2 D_0/\sigma$
We_N	*normal Weber* number, $We_N = \rho_l U_N^2 D_0/\sigma$
ρ^*	density ratio, $\rho^* = \rho_l/\rho_g$
μ^*	dynamic viscosity ratio, $\mu^* = \mu_l/\mu_g$

influence of the dimension of the superhydrophobic pillar arrays on the bouncing dynamics of water droplets. Compared to the previous studies with pillar arrays diameter less than 100 μm and height-diameter ratio larger than 10, "pancake bouncing" was also observed with pillar arrays of millimeter diameter and height-diameter ratio less than unity, which can be easily fabricated over large areas for industrial applications.

While most previous studies have focused on normal impact, oblique impact may occur more frequently in practice. Specifically, oblique impact differentiates from normal impact in the extra relative motion between the droplet and the surface in the tangential direction. Such relative tangential motion may rise frequently in practice due to either the tangential velocity of the droplet, *e.g.* a droplet is blown off course in a gaseous flow while falling down, or the tangential velocity of the surface, *e.g.* a droplet freely falls and impacts on a moving surface, or the inclination of the surface. In this regard, Šikalo et al. [25] investigated droplets impact on the inclined walls with contact angles ranging from 0° to 105°. It was found that the droplet tends to deposit on the surface at high impact angles, while rebound generally favors low impact angles. Yeong et al. [26] showed that although oblique and normal impact on to a nanocomposite superhydrophobic surface behave similarly at low normal *We* numbers (We_N), oblique impact exhibits obvious asymmetry at higher We_N, although the contact time is independent of surface inclination. Antonini et al. [27] further demonstrated that, inclined superhydrophobic surfaces could promote bouncing and decrease the contact time up to 40% while fixing the *Weber* number (*We*). For highly oblique impact, Aboud et al. [28] identified a new type of bouncing named "stretched rebound", in which droplets rebound while still being outstretched without tangential retraction. Zhang et al. [29] further demonstrated that "stretched rebound" is capable of reducing the contact time by 10–30% compared to conventional retracting bouncing. Three types of stretched rebound were also identified, in which the liquid detachment starts from front, center, and tail, respectively.

It should be nevertheless noted that, when a droplet impacts obliquely on a microstructured superhydrophobic surface, the impact dynamics could be largely affected by the impact angle that determines the relative importance between the tangential and the normal forces, the *We* number that measures inertia over surface tension, the *Oh* number that weighs viscous force against surface tension, as well as the microstructures on the surface. However, albeit of the worthy advances mentioned above, the droplet impact dynamics is still far from completely understood, and a comprehensive numerical study has never been attempted according to the authors' knowledge.

In the present study, we aim to numerically investigate the oblique impact dynamics of droplets on microstructured superhydrophobic surfaces, with particular interest in understanding different types of bouncing behavior and their effects on the contact time. The rest of the paper is organized as follows: the numerical method is introduced in Section 2, the results and discussion are given in Section 3, and the concluding remarks are finally made in Section 4.