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Drop impact on inclined superhydrophobic surfaces

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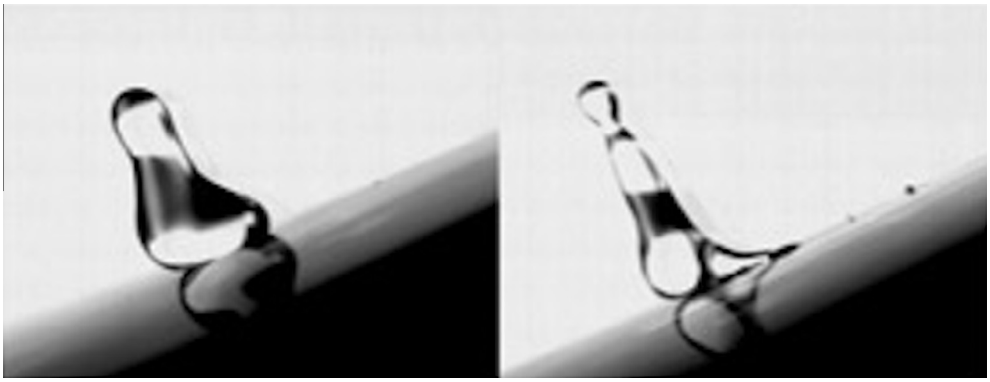
GRAPHICAL ABSTRACT



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ABSTRACT

This paper discusses the dynamic behavior of water drops impacting on inclined superhydrophobic surfaces. For a normal impact on a smooth hydrophobic surface, the spreading (or expansion) and retraction dynamics of an impacting drop varies from complete rebound to splashing depending on its Weber number, (We_d), calculated using the impact speed and diameter d of the drop. For a slanted impact, on the other hand, the impact dynamics depends on two distinct Weber numbers, based on the velocity components normal, (We_{nd}), and tangential, (We_{td}), to the surface. Impact on superhydrophobic surfaces is even more complicated as the surfaces are covered with micro- to nano-scale texture. Therefore, we develop an expression for an additional set of two Weber numbers, (We_{na}, We_{ta}), which are counterparts to the first set but use the gap distance a between asperities on the textured surface as the characteristic length. We correlate the derived Weber numbers with the impact dynamics on tilted surfaces covered with three different types of texture: (i) posts, (ii) ridges aligned with and (iii) ridges perpendicular to the impact direction. Results suggest that the first two Weber numbers, (We_{nd}, We_{td}), affect the impact dynamics of a drop such as the degree of drop deformation as long as the superhydrophobicity remains intact. On the other hand, the Weber number We_{na} determines the transition from the superhydrophobic Cassie–Baxter regime to the fully-wetted Wenzel regime. Accuracy of our model becomes lower at a high tilting angle (75°), due to the change in the transition mechanism.

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1. Introduction

The objective of this paper is to identify and empirically validate non-dimensional numbers that govern impact dynamics of drops on superhydrophobic surfaces. This can be done by investigating the relationship between characteristics both dependent and independent of the surface roughness and the transition between various impact patterns. A superhydrophobic surface has numerous micro- to nano-scale asperities between which the surface can retain pockets of air when in contact with water [1]. This air pocket leads to the formation of the solid–liquid–air composite interface, as explained by Cassie and Baxter [2], on which the wettability of a drop significantly decreases. This repellency against water drops has been utilized by natural and synthetic surfaces to achieve various interesting and useful functions, ranging from self-cleaning lotus leaves, non-wetting butterfly wings, to condensers with increased heat transfer coefficient [1,3–5]. When a Newtonian liquid drop impacts a superhydrophobic surface, the drop may display a complete rebound, partial rebound, or shattering of the drop depending on the initial kinetic energy of the drop and the surface tension of the liquid [6,7]. The most commonly used dimensionless number that compares the inertial effect and surface tension effect is the Weber number, $\left(We_d = \frac{\rho V^2 d}{\sigma}\right)$ [8]. Here ρ and σ are the density and the surface tension of a (Newtonian) liquid, V and d are the velocity and the diameter of the drop. We_d as defined is a legitimate predictor of bouncing patterns, as long as the impact is normal and the liquid–air interface between surface texture remains undisrupted throughout the impact [6]. In this non-wetting regime, an impacting drop remains on the surface when the We_d is low (due to insufficient kinetic energy for rebound because of viscous energy dissipation during the expansion and retraction), completely rebounds at intermediate We_d, and shatters at high We_d.

Such non-wettability is, however, limited by the robustness of the entrapped air pockets against the dynamic pressure of impacting drops. Indeed, although the rebound of a drop is predicted with higher We_d numbers, drops often rebound only partially when their Weber number exceeds a certain threshold value. This partial rebound regime occurs when the meniscus of impacting water drops can penetrate between the surface textures and disrupt the air pockets (see Fig. 1) [9]. It is possible that at high impact velocities, the dynamic pressure during the impact pushes the liquid–air interface to touch the troughs between the asperities and reside there in an equilibrium state, leading to the fully-wetted Wenzel regime [10]. The onset of this disruption depends on whether or not the amount of dynamic pressure of the drop is great enough to overcome the resistance due to the Laplace pressure from the bulging meniscus. Note that the length-scale relevant to this transition is the radius of curvature of the meniscus between the surface texture, not the diameter of the drop.

In this study, we identify and empirically validate the most adequate way to define a set of Weber numbers to predict a wetting transition for drops impacting superhydrophobic surfaces from arbitrary angles. A great deal of research has been done on the wetting phenomena on a superhydrophobic surface; most of this previous research focused on the quasi-static characteristics such as water contact angle, hysteresis, roll-off angle, and so forth [11–15]. These properties are primarily determined by the microscopic texture and chemistry of the surface [16,17]. Many attempts have also been made to develop, both by empirical and analytical means, a model that can predict the robustness of superhydrophobic surfaces to water penetration [18–22]. So far, it is well established that two distinct penetration mechanisms cause most of the wetting transitions [23]. The first type of wetting transition corresponds to the crossing of a critical pressure difference, driven by the dynamic pressure inside water drops. This type of failure occurs by destabilizing the triple-phase contact line (contact line where air, liquid, and solid converge) and subsequent penetration of the liquid–air interface into surface pores [23,24]. The second type of wetting transition can occur even when the contact line remains pinned to the top of the surface texture: any pressure differential across the liquid–air interface leads to the sagging of the interface, and if the bulging interface can touch the bottom of the texture, such a local wetting can quickly spread across the entire surface [20,23,25]. In both cases, the driving force for the transition is pressure, which, for the case of dynamic impact, originates from the transfer of momentum of the drop [18,26,27]. For example, a superhydrophobic surface may or may not repel an incoming drop depending on the relation between dynamic pressure (ρV^2; we refer readers to reference for the derivation of dynamic pressure from momentum transfer [33]) and the Laplace pressure created by the curvature and surface tension of water–vapor interface. As the Laplace pressure $P_{\text{Laplace}} = \kappa\sigma$ (κ is the curvature of the interface), and the maximum curvature of a water meniscus inside a pore is inversely proportional to the size of the pore ($\approx 1/a$; a represents the nominal size of air pockets or the interspacing between textures), one can define a dimensionless parameter by taking the ratio between two pressure terms. This dimensionless number $\left(We_a = \frac{\rho V^2 a}{\sigma}\right)$, resembling the traditional Weber number with a change in the choice of nominal length scale, can serve as a non-dimensional measure of potential penetration chance. For a

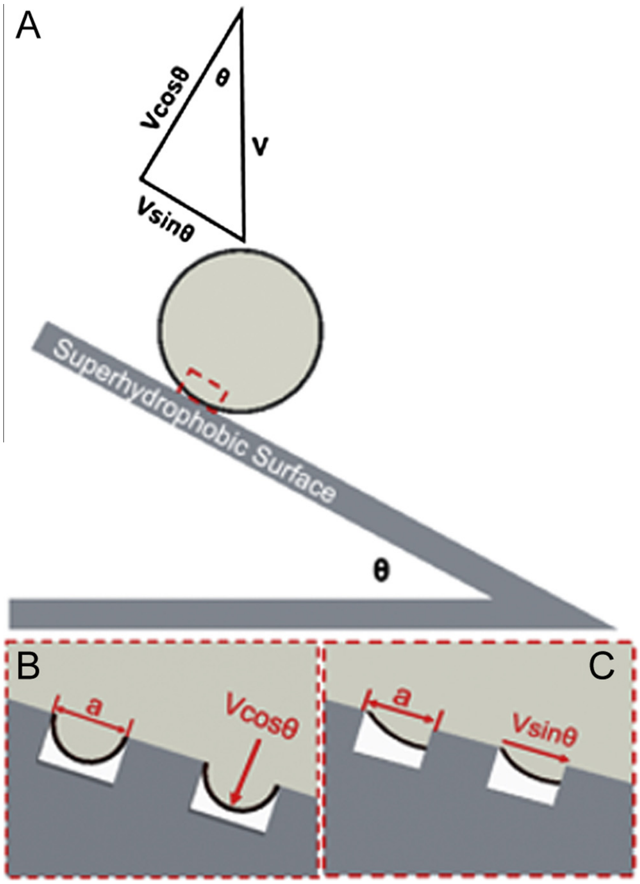

Fig. 1. Schematic of a drop impact: (A) decomposition of velocity into normal and tangential components. (B and C) Zoomed in view of the liquid–air interface showing the hypothetical bulging of the meniscus due to the velocity component normal to the surface (B; $V\cos\theta$) and tangential to the surface (C; $V\sin\theta$).