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MICROSCOPIC STRUCTURE INFLUENCING MACROSCOPIC SPLASH AT HIGH WEBER NUMBER

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Summary The dynamics of water drop impact at high impinging velocity onto superhydrophobic substrate is experimentally investigated. The solid substrate—comprised of regular and hydrophobic micropillars—is transparent, thereby facilitating close-up, top-or-bottom-view, high-speed imaging. With a sufficient impact velocity, instead of a completely-bouncing “Fakir" droplet, wetting splashing can occur, with an entrapped air bubble at the centre surrounded by a wetted area as well as an emission of satellite droplets during the advancing phase of spreading lamella. A large portion of the lamella travels upon air and subsequently recoils due to surface tension, forming a partial rebound on the central wet spot. We present and discuss quantitative results of the entrapped air bubble, the central wetted area, and the maximal spreading lamella as the impact velocity is increased. We further vary the lattice periodicity of the micro-patterns and find its profound influence on the macroscopic flow. More specifically, directional splashing can emerge, emitting secondary droplets in certain directions which are associated with the lattice. Directional splashing can be suppressed to a gentle spreading by decreasing the periodicity of the lattice and, furthermore, can be tuned to a completely-wetting splashing in the diagonal directions of the lattice by a larger periodicity, offering opportunities to control the wetting process. Finally, the elimination of directional splashing by reducing air pressure, P, suggests that the underlying air is squeezed outwards by the falling droplet upon the solid boundary whereby the air flow is affected, leading to different splashing behavior.

INTRODUCTION

Splashing impact, ejecting satellite droplets from the advancing lamella, for a liquid droplet hitting a solid surface has attracted enormous scientific and industrial endeavours and yet remains a puzzle. Several control parameters and their interplay make it difficult to reveal the underlying mechanism [1, 2, 3]. For example, not until recently have some unforeseen controls for eliminating a splash been discovered: with a reduction of the gas pressure [4, 5], an increase of the height of the microtextures [6], a decrease of the tension of an impinged elastic membrane [7], a tuning of the relative tangential velocity between a droplet and a dry, smooth surface [8], and, as we will see in this paper, a decrease of the periodicity length scale of a regular micropattern (see Fig. 1). In this study, we utilized transparent micropatterned solid surfaces to examine wether the entrapped air region exists. In addition, to fill the gap in the current literature of water drop impact on superhydrophobic substrate, impact dynamics at high speed was also investigated. Finally, the effects of the periodicity length scale of the regular micropatterns and the air pressure were examined.

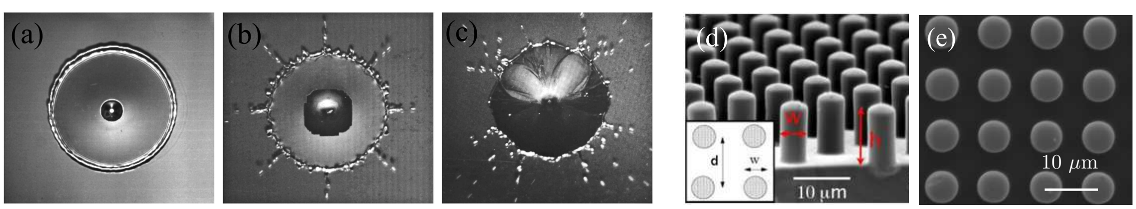

Figure 1. Bottom-view snapshots at 0.8 ms for a 1 mm radius water droplet impacting (at the speed of 3.7 ms^{-1} in the ambient pressure 1 atm) onto hydrophobic, square-latticed microstructures of three different periodicities of the constituent micropillars: (a) 7.3 μm, (b) 13.4 μm and (c) 22.4 $(\pm\ 0.5)$ μm, displaying the significant influence of the microscopic structure of the solid boundary on the macroscopic flow dynamics. (d) and (e) are representative Scanning Electron Microscope images of the used substrate, consisting of hydrophobic microcylinders (of the width w, and the height h) regularly arranged in a square lattice (of lattice periodicity d), under an angled view and top view, respectively.

EXPERIMENTAL SECTION

A Milli-Q water droplet was released from a fine needle at different heights, ranging from 10 to 200 cm, to vary the impact velocity. The targeted substrate consists of hydrophobic, polymeric micropillars (made of polydimethylsiloxane, PDMS) regularly arranged in a lattice, with the pillar width w, pillar height h, and the periodicity of the lattice d (see Fig. 1 (d) and (e)). The experimental setup was enclosed in a chamber, connected to a vacuum pump so as to control the ambient pressure of the surrounding air. The microstructures were fabricated with a micro-molding method by etching the inverse, desired micropatterns on a silicon wafer as a master replica mold. To examine the effect of micro-arrangments on the impact event, several molds were etched into cylindrical micro-holes with a certain depth h arranged in a square or a hexagonal lattice. We fixed the pillar width to be $5\ \mu m$ and varied the periodicity of the lattice unit d, spanning from 7.3 to $22.4\ \mu m$. Each sample had an areal dimension of $\approx 22.5 \times 22.5$ mm^2 fully decorated with regular micro-pillars. We express the main control parameter, the impact velocity, by the Weber number $We = \rho R V^2/\sigma$, the ratio of the kinetic

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energy to surface energy, with the liquid density ρ, the drop radius R, the impact velocity V, and the liquid surface tension σ. Our largest explored We-number reaches O(10^3), about one order of magnitude larger than that hitherto reported in the literature for superhydrophobic surfaces.

RESULTS AND DISCUSSION

The effect of microstructures

The geometric arrangement of the hydrophobic micropillars has been shown to affect the critical impact velocity below which a water droplet completely bounces off the superhydrophobic surface at low Weber number O($1-10$) [10]. In this study, we further showed the influence of microstructures on splashing at Weber number. We found that when a water drop impacts on certain regular microtextured surface, splashing is promoted in certain directions, which are strongly correlated with the lattice arrangement. Here, this type of splashing is referred to as *directional* splashing. In addition, the shape of the central wetted area was influenced by the geometric arrangement of micro-pillars.

The influence of air pressure

The crucial influence of air pressure on the splash has recently been verified for *wetting* (ethanol) droplet impacting onto both smooth [4] and (micrometer-sized) rough [5] surfaces. Corona splash on smooth glass plate can be eliminated under a lower pressure [4], whereas some prompt splashes on extremely rough or porous surfaces survive [6, 9]. Here we further examine the effect of the surrounding air pressure, P, on the *directional* splash for *non-wetting* (water) droplet impinging on hydrophobic micropillars in a regular lattice. At 1 atmospheric air pressure (P = 101.3 kPa), clear directional splash appears in a sixfold symmetry. In addition, the central darker wetted area remained a steady hexagon, even during the advancing phase of the spreading lamella. From the close-up images, a tiny bright spot at the centre can be noticed; this can be an indication of the dimple of the droplet when in contact with the bottom of the microstructured surface. Besides the wetted regions at the centre, a large amount of liquid actually surfs on air, which appears brighter in the images. In contrast, a decrease in air pressure can suppress the directional splash: At P = 58 kPa, only a small fraction of the splash is presence. Below P = 48 kPa, no advancing directional splash appeared, and the liquid spread to a less extension without the present of air. As a result, the maximal spreading diameter not only depends on We but also on the air pressure P.

CONCLUSIONS

In contrast to a complete rebound at low We, the impact dynamics at high We is featured with an advancing splash, wetting a central area which encloses an air region, subsequently with receding breakups of fingering lamella, and finally with a partial rebound rooted at the central wet spot. The entrapped air disk shows an insignificant dependence on We and spans about $\lesssim 15$ % of the drop size D. For a sufficient impact velocity ($We \gtrsim 20$), the central wet area exists and moreover is enlarged as the impact velocity is increased, and splashes occur for $We \gtrsim 235$ (based on D = 2 mm, and for micropatterns of $d = 10$ μm). However, in comparison to the input kinetic energy the surface energy required for the wet area occupies a small fraction and is decreased as We is increased. We found that for large $10^2 < We < 10^3$ the maximal spreading lamella scales as $We^{1/4}$, the same exponent found previously for small We region on both superhydrophobic and hydrophilic surfaces. We further discovered a large influence of air pressure on the maximal spreading diameter on hydrophobic microtextures; The maximal diameter of the spreading lamella decreases and directional splash can be eliminated with a decreasing P. Most importantly, we found a profound effect of microtextures on macroscopic splash that provides convenient means to control splash and its directions.

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