Experimental Thermal and Fluid Science 74 (2016) 195–206

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Droplet impact dynamics on micropillared hydrophobic surfaces

Nagesh D. Patil, Rajneesh Bhardwaj [*], Atul Sharma

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 20 June 2015
Received in revised form 3 November 2015
Accepted 20 December 2015
Available online 28 December 2015

Keywords:
Droplet impact dynamics
Micropillared surfaces
Non-bouncing
Complete bouncing
Partial bouncing
Cassie to Wenzel wetting transition

ABSTRACT

The effect of pitch of the pillars and impact velocity are studied for the impact dynamics of a microliter water droplet on a micropillared hydrophobic surface. The results are presented qualitatively by the high-speed photography and quantitatively by the temporal variation of wetted diameter and droplet height. A characterization of the transient quantitative results is a novel aspect of our work. Three distinct regimes, namely, non-bouncing, complete bouncing and partial bouncing are presented. A critical pitch as well as impact velocity exists for the transition from one regime to another. This is explained with demonstration of Cassie to Wenzel wetting transition in which the liquid penetrates in the grooves between the pillars at larger pitch or impact velocity. The regimes are demarcated on a map of pitch and impact velocity. A good agreement is reported between the present measurements and published analytical models.

1. Introduction

Understanding impact dynamics of bouncing and non-bouncing droplets on hydrophobic and superhydrophobic surfaces is useful in several technical applications. These surfaces exhibit low wettability and this property may be leveraged in the applications such as pesticide spray coating [1], drag reduction [2], anti-snow adhesion surfaces [3], self-cleaning surfaces [4], and surface cooling via spray evaporative cooling [5] and on spatially varying wettability surfaces [6]. The fluid and interface dynamics during the droplet impingement on a solid surface is highly transient. For instance, impact of a 3 μl isopropanol droplet with 0.37 m/s velocity takes around 7 ms to spread on a heated fused silica surface [7]. The liquid–gas interface exhibits capillary forces and dynamic wetting occurs at the contact line. During the impact, the droplet first spreads and the contact line recedes later, which may lead to the bouncing on surface with lower wettability. The advancing/outward motion is aided by the momentum or inertia-force during the spreading and is resisted by the surface tension and viscous forces. After the maximum spreading, the surface energy leads to the receding/inward motion of contact line and recoiling of the liquid–gas interface. During the change from advancing to receding motion of the contact line, the contact line is pinned to the surface and dynamic contact angle reduces from advancing to receding. Thus, the droplet fate depends on the interplay of several forces namely, inertia, viscous, surface tension and gravity, and surface wettability. The fate could be spreading/non-bouncing, partial bouncing, complete bouncing or splashing depending on the impact conditions and surface wettability (see review by Yarin [8]).

Previous experimental studies extensively investigated the droplet bouncing and non-bouncing on the hydrophobic as well as superhydrophobic surfaces. For instance, Richard and Quéré [9] recorded several bouncing cycles of a 1 mm water droplet on a superhydrophobic surface, with advancing contact angle of 170°. Similarly, Rioboo et al. [10] studied the effect of surface tension, viscosity and density on the surface with different wettabilities and found that the receding angle and surface roughness are two important parameters in deciding the bouncing. Renardy et al. [11] studied the bouncing of water droplets on superhydrophobic surfaces; and reported pyramidal as well as toroidal shapes of the droplet, after it bounces off at low and moderate impact velocities. They discussed internal swirling flow and thin film formation at the impact location. Clanet et al. [12] studied the bouncing of a 2.5 mm water droplet impacting with a velocity of 0.83 m/s on a superhydrophobic surface with equilibrium contact angle of 170°. They studied the maximum spreading of droplet for wide range of Weber numbers and proposed a model for the maximum width of the deforming droplet. Further, Antonini et al. [13] analyzed the droplet spreading and receding characteristics, during its impact on the hydrophilic to superhydrophobic surfaces for wider range of advancing contact angles (48–166°).

In the last decade, the droplet dynamics was investigated on engineered micropillared surfaces which exhibit varied surface wettability as a function of pillar diameter, pillar height and pitch. An important issue is the wetting transition from Cassie [14] to

---

[*] Corresponding author. Tel.: +91 22 2576 7534; fax: +91 22 2576 6875.
E-mail address: rajneesh.bhardwaj@iitb.ac.in (R. Bhardwaj).

http://dx.doi.org/10.1016/j.expthermflusci.2015.12.006
0894-1777/

Nomenclature

Symbols

D_0	initial droplet diameter (m)
D_{max}	non-dimensional maximum droplet width/diameter
D_{wetted}	non-dimensional droplet wetted diameter
$D_{wetted_{max}}$	non-dimensional maximum droplet wetted diameter
H_{max}	non-dimensional maximum axi-symmetric droplet height
Oh	Ohnesorge number
p_d	dynamic pressure (Pa)
p_c	capillary pressure (Pa)
p_{EWH}	effective water hammer pressure (Pa)
P	pitch of the pillars (μm)
Re	Reynolds number
t	time (s)
t_{osc}	time-period of the free surface oscillation for non-bouncing droplet (s)
t_b	contact time for bouncing droplet (s)
U_0	impact velocity of a droplet (m/s)
We	Weber number

Greek letters

γ	surface tension (N/m)
θ_{adv}	advancing contact angle (°)
θ_{eq}	equilibrium contact angle (°)
θ_{mqs}	quasi-static contact angle at the maximum spreading (°)
θ_{rec}	receding contact angle (°)
θ_H	contact angle hysteresis (°)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Wenzel [15] state on such surfaces. The air gets trapped between the micropillars in the former while the liquid fills the complete region between the pillars in the latter. The characterization of the wetting transition was investigated in several studies without or with impact dynamics. For instance, the transition was recorded by increasing droplet volume [16], by evaporating sessile droplet [17–20] and, by varying the pillar pitch [18,21] as well as pillar shape [22]. In the context of the reporting the effect of the wetting transition on the impact dynamics, previous studies showed that the wetting transition from Cassie to Wenzel state changes the droplet fate from bouncing to non-bouncing. For example, by varying the equilibrium contact angle of a carbon nanotube arrays [23], impact velocity [24–28], pillar diameter [25,29] and, pillar height and pitch [24,25,27].

The wetting transition described above was explained by first order analytical models. For example, Bartolo et al. [24] suggested that the transition occurs if dynamic pressure due to inertia (p_d) exceeds capillary pressure due to surface tension (p_c). Oftentimes, the partial bouncing was also recorded at larger impact velocities due to the partial penetration of the liquid in-between the pillars. Deng et al. [30] explained it using effective water hammer pressure (p_{EWH}) which generates due to the compression of droplet by shock wave at larger impact velocity. According to authors, the criteria for non-bouncing, complete bouncing and partial bouncing are $p_{EWH} > p_d > p_c$, $p_c > p_{EWH} > p_d$ and $p_{EWH} > p_c > p_d$, respectively. Further, Dash et al. [31] demonstrated a high capillary pressure for hollow square pillars in comparison with solid square pillars. They tested the stiffness of surfaces using a dynamic pressure and water hammer pressure, and showed that water hammer pressure depends on the surface morphology. Maitra et al. [32] showed that the fate of droplet partial bouncing or impalement on a pillared surface happened because of air compression (due to water hammer pressure) beneath the droplet. Very recently, Meng et al. [33] characterized the fate of droplet on three-level of hierarchical surfaces with varying pillar height. Their analysis showed that varying height and shape of micro-pillars can reduce the water hammer pressure and restricts the possibility of water penetration in-between the pillars.

As mentioned above, although there are numerous studies on the effect of surface morphology of the micropillared surfaces on the impact dynamics, there was almost no study on the effect of systematic variation of pillar pitch at various impact velocity. For example, pillar height, pillar diameter and pitch were varied simultaneously in Refs. [24,25] and Tsai et al. [27] considered a smaller range of variation of pitch (1.8–7 μm) for a 5 μm square pillar. The present work considers the independent variation of pitch (30–76 μm) and impact velocity (0.22–0.62 m/s), at a constant cross-sectional dimension of 20 μm and height of 27 μm, for the square pillars. We discuss the three distinct droplet fates, namely, non-bouncing, complete bouncing and partial bouncing, measured for the above mentioned range.

To this end, the present experimental work has four objectives. First, perform a detailed qualitative as well as quantitative transient image (obtained from high speed visualization) analysis for various pitches of the pillars and the impact velocity; and study the role of surface wettability as well as kinetic energy and surface energy on the impact dynamics. Second, propose a regime map which demarcates various impact dynamics regimes in impact velocity-pitch plane. Third, demonstrate the droplet wetting transition from non-penetration to partial penetration to complete penetration of the droplet liquid in-between pillars; and analyze the corresponding outcome to non-bouncing/complete bouncing/partial bouncing. Fourth, propose a correlation for the maximum wetted diameter based on present measurements.

2. Experimental methods

2.1. Fabrication and characterization of micropillared surfaces

Micropillared surfaces are fabricated using ultraviolet lithography [34], after depositing SU-8 2025 epoxy photoresist polymer on polished side of 2 inch silicon wafer. This is done in a five-step process. First, Si wafer was cleaned by RCA cleaning process and wet oxidized in a furnace to remove suspended or dissolved components. Second, SU-8 was spin-coated on the wafer with a speed of 500 rpm for 10 s and 2300 rpm for next 40 s. Third, the wafer was soft-baked at 65 °C for 3 min and at 95 °C for next 8 min. An iron oxide coated glass mask with square-shaped patterns (printed using Laser Writer, LW405, Microtech Inc.) was aligned on the top of spin-coated wafer using double sided aligner (EVG620, EV Group Inc). The wafer was exposed to UV radiation with intensity of 160 mJ/cm^2 for 2–3 min. Fourth, the samples were post-baked at 65 °C for 1 min, 95 °C for next 6 min and allowed to cool in ambient. Subsequently, they were developed in SU8 photo developer for 5–6 min and cleaned by isopropanol. Fifth, the wafer was kept on a heater at 120 °C for 10 min for hard-baking and surfaces were coated with 10 nm platinum layer. Two different views of the fabricated surfaces – recorded by SEM – are shown in Fig. 1(a), for several pitches; pitch is the distance between centers of two