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An experimental study on the equilibrium shape of water drops impacted on groove-textured surfaces

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ABSTRACT

Understanding the final shape of liquid drops deposited on groove-textured surfaces is a significant aspect of many applications (for example, liquid drainage). This is lacking in literature, especially for drop impact on micro-textured surfaces. The effect of drop impact velocity and groove-texture geometry on the final shape adopted by water drops impacted on groove-textured surfaces is reported here. Water drops gently placed on groove-textured surfaces comprising trapezoidal (rectangular) pillars adopted the Wenzel (Cassie) state. Top view images of final equilibrium shape of water drops impacted on the groove-textured surfaces revealed a contrasting behavior between Wenzel and Cassie surfaces. At low impact velocity, the final drop shape on Wenzel surface is elongated more in the direction parallel to the grooves than perpendicular to grooves thereby exhibiting anisotropy whereas on Cassie surface the final drop shape is almost isotropic. As impact velocity increases, the anisotropy in final drop shape on Wenzel surface decreases whereas on Cassie surface it increases. The final drop spread factors and contact angles measured perpendicular and parallel to grooves show contrasting trends with impact velocity between Wenzel and Cassie surfaces. This is modelled through the difference between drop receding perpendicular and parallel to the grooves, resulting from a difference in liquid drop impregnation state, between the surfaces.

1. Introduction

Interaction of liquid drops with solid surfaces is seen in a number of practical scenarios [1–3]. The final outcome of interaction of a liquid drop with a solid surface could be one of the following: deposition, bouncing, splashing [1,2,4]. When a liquid drop is deposited on a solid surface as a result of the interaction process, it generally takes the form of a spherical cap (when the corresponding contact angle, $\theta_f \neq 0$) or a thin film (when $\theta_f = 0$). Understanding this equilibrium shape of the liquid drop on solid surface is relevant from the point-of-view of understanding post-impact processes such as evaporation of drop on the solid surface. The equilibrium shape adopted by a liquid drop on a solid surface is usually quantified in terms of its contact area (expressed in terms of contact diameter, D_f) with the surface and contact angle, θ_f. It is, in general, a function of numerous parameters [1–3]:

(i) Physical properties of drop liquid (surface tension, σ; dynamic viscosity, μ; and density, ρ).
(ii) Size of liquid drop specified by its diameter, D_o, and its impact velocity, U_o.
(iii) Physical and chemical characteristics of the target solid surface specified respectively by the roughness parameters and Young's contact angle of liquid drop on the surface material, θ_Y.

The broad focus of the present study is on the combined effect of surface texture geometry (physical characteristics) and drop impact velocity on the final equilibrium shape of liquid drops on solid surfaces.

The effect of surface characteristics on the equilibrium shape of liquid drops gently deposited on the surface (static wetting) has been the subject of various studies for the last couple of decades, mostly due to the progress in micro- and nano-fabrication techniques [5]. For example, on surfaces uniformly textured with well-defined linear grooves parallel to each other, referred to as groove-textured surfaces, a gently deposited liquid drop takes an

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Nomenclature

Symbol	Definition (Units)
a	fitting coefficient in the expression, $\beta_{f,\perp} = aWe^b$ (Dimensionless)
A	fitting coefficient in the expression, $\beta_{f,\|\|} = AWe^B$ (Dimensionless)
b	fitting exponent in the expression, $\beta_{f,\perp} = aWe^b$ (Dimensionless)
B	fitting exponent in the expression, $\beta_{f,\|\|} = AWe^B$ (Dimensionless)
d	groove depth of groove-textured surface (μm)
D_f	final spread diameter of liquid drop impacted on solid surface (mm)
D_o	diameter of liquid drop just prior to impact (mm)
e_f	elongation factor of final drop spread during liquid drop impact on groove-textured surface (Dimensionless)
$g*$	effective deceleration of impacting drop normal to the target surface (m/s^2)
h	thickness of receding drop rim (mm)
H	height of needle tip from the target surface (mm)
r	Wenzel roughness factor of groove-textured surface (Dimensionless)
t_c	inertio-capillary time scale (ms)
U_o	impact velocity of liquid drop (m/s)
$U_{o,cr}$	critical drop impact velocity at which drop liquid impregnation into groove occurs during impact on groove-textured surface (m/s)
U_r	receding velocity of drop front on solid surface during liquid drop impact on solid surface (m/s)
w_g	groove top width of groove-textured surface (μm)
w_p	pillar top width of groove-textured surface (μm)
We	Weber number of impacting liquid drop (Dimensionless)

Greek symbols

α	pillar/groove side angle of groove-textured surface (degrees)
β	instantaneous drop spread factor during impact on solid surface (Dimensionless)
β_f	final drop spread factor during impact on solid surface (Dimensionless)
β_m	maximum drop spread factor during impact on solid surface (Dimensionless)
$\Delta\beta$	difference between maximum and final drop spread factors (Dimensionless)
$\Delta\theta_f$	anisotropy in final drop contact angle during impact on groove-textured surface (degrees)
ϕ	solid fraction of groove-textured surface (Dimensionless)
μ	dynamic viscosity of liquid constituting the drop (mPa s)
ρ	density of liquid constituting the drop (kg/m^3)
σ	surface tension of liquid constituting the drop (mN/m)
θ_a	advancing contact angle of liquid drop on target surface measured from static wetting experiments (degrees)
θ_e	equilibrium contact angle of liquid drop on target surface measured from static wetting experiments (degrees)
θ_f	final contact angle of liquid drop impacted on solid surface (degrees)
θ_r	receding contact angle of liquid drop on target surface measured from static wetting experiments (degrees)
θ_Y	Young's contact angle of liquid drop on a flat, smooth surface (degrees)

Subscripts

$\|\|$	measurements made in the front view plain parallel to the grooves on groove-textured surface (–)
$\perp$	measurements made in the front view plain perpendicular to the grooves on groove-textured surface (–)

anisotropic shape which is elongated parallel to the grooves and pinned perpendicular to grooves [6–16]. Here we explore and study the effect of drop impact velocity on the final equilibrium shape of liquid drops on groove-textured surfaces. This is motivated by the fact that most of the scenarios in which liquid drops interact with solid surfaces involve drop impact velocity. Except for a few studies [7,8,11,14,16], the current literature lacks conclusive results for the case of groove-textured surfaces widely seen in practical scenarios involving directional liquid drainage [13], micro-finned heat exchanger surfaces [10,11,13], and in nature on rice plant leaves [16].

In contrast to the case of gentle deposition of a liquid drop on a solid surface, drop impact results in drop spreading which is immediately followed by receding process. The presence of spreading and receding processes makes the understanding and theoretical prediction of final equilibrium drop shape complicated since it involves separately modelling them. Most of the studies, limited to drop impact on un-textured/flat surfaces, use either of the following two approaches to theoretically model the final equilibrium drop contact diameter on solid surface:

(i) **Use mass conservation** with an assumption that the final equilibrium contact angle is the same as the static equilibrium contact angle, θ_e measured from static wetting (gentle deposition) studies [17]. This approach is used mostly for liquid drop impact on un-textured/flat surfaces till now.

(ii) **Consider maximum drop spread on the target surface as equivalent to the final drop spread** [18]. In this, the maximum drop spread is generally modelled through an energy conservation based approach [19–21] (although it has limitations [22]) or through an approach which uses an 'effective gravity' to describe the drop deceleration [23]. This approach is suitable only for cases when the impacting drop undergoes negligible receding on target surface and has been used mostly for liquid drop impact on un-textured/flat surfaces.

The impact dynamics is more complex on micro-textured surfaces, esp. on groove-textured surfaces due to the inherent anisotropy of the texture [7,8]. Most of the experimental studies of drop impact on micro-textured surfaces dealt with some of the following aspects of drop impact dynamics: maximum drop spread [14,24–26], transition from Cassie to an impregnated or Wenzel state [27–29], contact time of drops on superhydrophobic micro-textured surfaces [30,31], and regimes of drop impact dynamics based on morphological dynamics of impacting drop and drop impact outcome [26,32]. Miscellaneous phenomena such as jetting from the center of drops impacted on groove-textured surfaces [14] and a rhombus-shaped spreading pattern of drops impacted on micro-textured surface [24] were also reported. Even though these studies cover a variety of aspects related to drop impact dynamics on micro-textured surfaces, the final equilibrium shape of deposited drops and its trend with surface texture geometry