Journal of Industrial and Engineering Chemistry xxx (2016) xxx–xxx

ELSEVIER

Contents lists available at ScienceDirect

Journal of Industrial and Engineering Chemistry

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

Review

Droplet impact on superhydrophobic surfaces: A review of recent developments

Q1 Danial Khojasteh[a], Nooshin Moradi Kazerooni[b], Sahba Salarian[a], Reza Kamali[a,*]

[a] *School of Mechanical Engineering, Shiraz University, Shiraz 71936-16548, Iran*
[b] *School of Chemical and Petroleum Engineering, Shiraz University, Shiraz 71348-51154, Iran*

ARTICLE INFO

Article history:
Received 11 June 2016
Received in revised form 19 July 2016
Accepted 22 July 2016
Available online xxx

Keywords:
Droplet impact
Superhydrophobic surface
Wettability
Droplet deformation
Q3 Inclined surface
Contact time

ABSTRACT

A comprehensive understanding of the dynamics of droplets undergoing collisions with solid surfaces is required in a number of technological and industrial situations. Recently, a new kind of functional surface with particular characteristics has attracted increasing attention among the scholars and industrialists. Besides the thirst for knowledge, researchers have been driven by the possible applications of drop impinging superhydrophobic materials in several fields, such as self-cleaning, ice resisting, corrosion protection, etc. Hence, even the least improvement in understanding the underlying physics of droplet impacting superhydrophobic surfaces is of profound significance. Consequently, this paper presents a brief review of potential applications of superhydrophobic surfaces. The special feature of this study is to thoroughly focus on the most recent advances regarding dynamics and kinematics of drop impinging superhydrophobic substrates. On this account, the latest scientific findings in droplet impact and its deformation plus the effects of surface characteristics have been surveyed exhaustively.

Contents

Introduction

The dynamics of liquid droplets impacting a solid surface, which was coined by Worthington [1], have fascinated a lot of interest among scholars in recent years. Today, even the least improvement in understanding the fundamentals of a drop characteristics after impinging a surface is sorely favorable, concerning the remarkable wealth of its application in industry and material science. A fundamental application of droplet impinging is spray cooling, which is a promising candidate to provide high rate heat transfer [2,3]. Inkjet printing is another proven methodology for drop-on-demand pattern formation based on the physics of the droplet [4–6]. Droplet-based microfluidic is also a rapidly emerging technology with considerable impact on biomedical diagnostics, food and chemical industries [7–12]. In combustion chambers, droplet impact plays a decisive role when the fuel droplets impinge on the walls [13]. Anti-icing property of superhydrophobic (SH) coatings can be applied in aerospace and power industries including aviation, power lines, insulators and helicopter blades, which is due to the fact that water

---

Q2 * Corresponding author. Fax: +98 7136473511.
E-mail addresses: rkamali@shirazu.ac.ir, rezakamaly@yahoo.com (R. Kamali).

http://dx.doi.org/10.1016/j.jiec.2016.07.027

Please cite this article in press as: D. Khojasteh, et al., Droplet impact on superhydrophobic surfaces: A review of recent developments, Journal of Industrial and Engineering Chemistry (2016), http://dx.doi.org/10.1016/j.jiec.2016.07.027

droplets on the SH surface are easy to leave the surface when the surface is slightly tilted or blew by natural wind [14–24].

There is a diverse range of other notable applications in engineering fields including spray painting and coating, liquid atomization, trickled bed reactors, erosion of turbine blades and aircrafts, fire suppression, refrigerated cycles and retarding ice formation on surface of heat exchangers [25–31]. Drop impact on solid surfaces has also been extensively discussed with respect to many natural phenomena e.g., self-cleaning which has excited the scientists' curiosity since the discovery of water repellency properties of lotus leaves [32]. Other applications to be mentioned are: soil erosion, atmospheric and oceanographic science, formation of central peaks in craters and acid rain impacting leaves. Contemplating the variety of application areas, comprehensive studies on distinct features of drop impact seems essential [28,33,34].

Different phenomena arise during drop impaction on a solid surface such as deposition, receding, splashing and rebound [25]. Possible scenarios were comprehensively reviewed in the work of Rein [33], Yarin [25], Marengo et al. [35] and recently Josserand and Thoroddsen [36]. The outcome of impacting drop is affected by various factors including droplet properties (viscosity, density, surface tension, etc.), kinematic parameters and surface characteristics that can be altered by surface roughness or texturing [34,37–40]. To account for these factors dimensionless parameters have been employed to investigate drop impact dynamics among which Reynolds number, $Re = \rho u_0 d_0/\mu$, Weber number, $We = \rho u_0^2 d_0/\sigma$, Capillary number, $Ca = \mu u_0/\sigma$ and Ohnesorge number, $Oh = \mu/\sqrt{\rho \sigma d_0}$ are the most crucial numbers, where u_0 is the impact velocity, d_0 is the initial drop diameter and ρ, μ and σ are liquid density, viscosity and surface tension, respectively [35,41–43].

One of the most influential parameters during impact on solid substrates is wettability of the target surface which is controlled by surface energy due to the molecular structure seen in the top layer of the surface in addition to surface roughness [44,45]. The wettability is commonly specified by the contact angle (CA) of a water droplet on a solid surface. Two models have been introduced to elucidate the state of water on solid surfaces: Wenzel [46] state and Cassie–Baxter [47] state. In the case of Wenzel scenario, the water penetrates into the structured surface and the water droplets conform to the surface, while in Cassie–Baxter state, liquid droplets retain an almost spherical shape and can easily roll off the surface. Apparently, Cassie–Baxter state provides larger contact angle in comparison to Wenzel state, as illustrated in Fig. 1 [48–50]. The behavior of a droplet on rough hydrophobic (H) surfaces is described by the two aforementioned models. Surfaces with high water repellency (H) exhibit contact angles ranging between 90–150° and surfaces with very high water repellency (superhydrophobic) have contact angles greater than 150°, offering special non-wetting properties [51].

Hydrophobic surfaces can be created by employing low surface energy materials or coatings such as tetrafluoroethylene or wax. Hydrophobicity can also be enhanced through roughening the surface or creating air pockets [27]. In recent years significant attention has been attracted to the development of SH surfaces by combining hydrophobicity with surface roughness [2,35]. SH surfaces frequently have a hierarchically double-scale (micro- and nanoscale) structures which particularly consist of nanoscale pillars on microscale domes. Hence, advancement in micro and nanofabrication technology has led to great achievements in generating a variety of surfaces with tailored wettability and physical morphology [52,53]. These surfaces increase the mobility of drops by reducing their contact-angle hysteresis and decreasing drag in both laminar and turbulent flows by supporting a shear-free air–water interface over which water slips [54]. Due to the negligible viscous dissipation engendered by the air pockets trapped at the interface, drop impact on SH surfaces usually manifests a complete rebound, a partial rebound or shattering of the drop, depending on the impact velocity and liquid properties. These parameters characterize the inertial and surface tension effects, both evaluated through the Weber number, which can predict bouncing patterns for normal impact, as along as the liquid–air interface between surface textures remains disrupted [50,55,56]. When a moving drop impinges on SH surfaces, the inertial energy is converted to interfacial energy causing the drop to spread and deform. Rebound characteristics are governed by the extent of energy dissipation during impact and wetting transition within the structure, since the drop may stick on the surface, unable to rebound [51,55,57,58].

Technological potential for various characteristics of SH surfaces and its position in drop impaction in addition to the rapid increase in publications on this issue over recent years, have necessitated a comprehensive review to elucidate the underlying physics of drop impingement onto SH surfaces which is lacking in the current extensive literature. The scope of this review is to provide a panoramic overview of recent contributions in the broad area of dynamics and kinematics of drop impact on SH substrates. In what follows, novel approaches for fabrication of SH surfaces in addition to its existing and potential applications are briefly surveyed. The following outlines also include latest scientific findings related to dynamics of impact and the arising phenomena, effects of surfaces with distinct morphologies and features, outcome of drop impingement on inclined surfaces and contact time. Although it was infeasible to aim at a total coverage, considering the multitude of recent reports, a representative subset of the latest progresses was selected to focus on. We hope our survey can contribute to guide an interested reader through the massive literature.

Fabrication and application of superhydrophobic surface

Recently, structures with specific characteristics such as hydrophobicity and adhesion has attained considerable interest among researchers. Moreover, their significance to the behavior of natural systems and interfacial fluid dynamics represents a rapidly growing area [59]. SH surfaces, as mentioned before, are defined as surfaces with water contact angles particularly larger than 150° with contact-angle hysteresis less than 10 °C [60,61].

In nature, such surfaces are found among large surfaces with nanoscale outer-layer wax and low substrate energy [56] among which, lotus leaves [62], butterfly wings [63,64], cicada's wings [65], rose petals [66] and mosquito eyes [67] were the most inspiring ones for artificial fabrication of SH materials. In the last few years, various techniques have been presented to add superhydrophobicity to a surface, including etching [68–71], sol–gel coating [72–75], spray coating [76], anodic oxidation [77,78], galvanic deposition [79,80], lithography [81–83], electrospinning [84–87], hybrid [88] and layer-by-layer process [59,89,90]. Some images of nano-fabricated textures creating superhydrophobicity caused by pocketed air are indicated in Fig. 2 [91]. Although there are numerous methods for manufacturing SH surfaces, only few of them are commercially available for practical applications due to their poor chemical and mechanical stabilities [92]. The SH surfaces have attracted continued attention for their broad range of applications among which are water droplet condensation and evaporation [93–97], anti-icing [22,98–100], oil-repellency [101], anti-corrosion [101–103], self-cleaning [22,64,103–106] and drag reduction [107–110] purposes. Some properties and applications of such surfaces are presented in Fig. 3 [111–114].

Merging superhydrophobicity with other features such as tunable wettability, transparency and anti-dew properties, is also a

Please cite this article in press as: D. Khojasteh, et al., Droplet impact on superhydrophobic surfaces: A review of recent developments, Journal of Industrial and Engineering Chemistry (2016), http://dx.doi.org/10.1016/j.jiec.2016.07.027