Experimental Observation of Droplet Impact Dynamics on Superhydrophobic Elastic Membranes

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Abstract
This experimental study investigates the impact dynamics of water droplets on superhydrophobic elastic membranes, revealing that substrate flexibility significantly enhances droplet retraction and reduces contact time through elastic energy storage and release mechanisms. Using ultrafast imaging and force sensing across varied impact velocities, membrane elastic moduli, and droplet parameters, we demonstrate a nonlinear decrease in contact time with increasing velocity, culminating in droplet scattering beyond a critical threshold. The flexible membranes promote springboard-like lift-off, converting stored elastic energy into vertical momentum, unlike rigid surfaces. These findings establish design principles for advanced self-cleaning, anti-icing, and water-harvesting surfaces where mechanical compliance governs dynamic wetting behavior.

Keywords: Droplet impact dynamics; Superhydrophobic surfaces; Elastic membranes; Self-cleaning surfaces
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1. Introduction

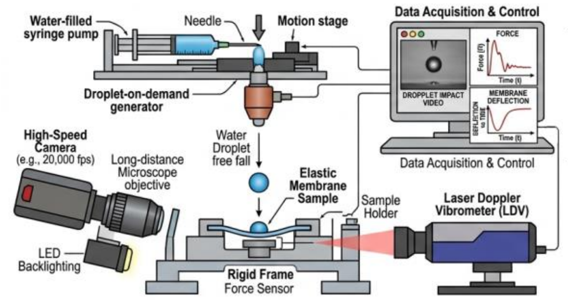
The dynamics of droplet impact on solid surfaces are among the fundamental basics in fluid physics and surface engineering due to their wide repercussions in many fields, such as industrial cooling, ink-jet printing, protective coatings, and accurate applications of aviation and agriculture [1-6]. With developing surface fabrication techniques, the superhydrophobic surfaces have emerged as a revolutionary solution due to their ability to reduce the contact time and friction forces as well as to enhance the self-cleaning property. Therefore, these surfaces were reasonably interested by both academic and industrial institutions [7-12]. However, most previous studies have focused on the solid surfaces and ignored the fact that many practical applications depend on flexible or elastic substrates subjected to instantaneous mechanical distortions during the impact process [13-18].

Accordingly, the significance of this work is to bridge the current knowledge gap throughout proposing an accurate experimental observations for the behavior of droplets impacting flexible superhydrophobic membranes as the hydrodynamic effects intertwine with the mechanical response of the carrier materials [19-23]. The interaction between the droplet and the flexible membrane imposes a complex physics equation not only including diffusion parameters, retraction, and contact angles, but also extends to the distortion coefficient of the flexible membrane, energy transfer between droplet motion and substrate vibrations, and the effects of material's characteristics, such as Young's modulus and membrane thickness, on the timing and nature of different impact stages [24-27].

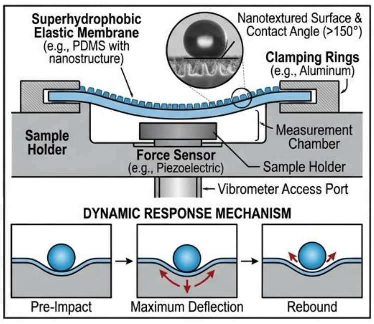
The integrated understanding of these dynamics can prepare for new designs of controllable smart systems, such as anti-freeze surfaces, water-collecting devices from the fog, and elastic microfluidic devices. To achieve that, this work is based on an experimental methodology combining the ultrafast imaging and precise force probes to produce a comprehensive description of the affecting variables with highlighting the nonlinear phenomena originating when the elasticity and superhydrophobicity are exchanged.

2. Experimental Part

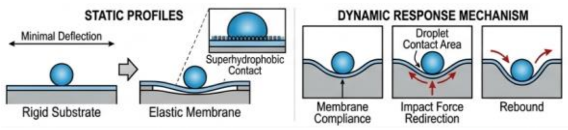
Figure (1) shows schematically an overview of the experimental setup (section A), the fabricated cross-section device structure (section B) proposed in this work, membrane properties and mechanism (section C), and measurement and data analysis (section D). The experimental work was based on designing an integrated experimental setup for synchronized measurement for both the droplet and the response of the superhydrophobic flexible membrane at the moment of the impact. Flexible membranes were prepared from the poly dimethyl siloxane (PDMS) with different mixing rations to obtain different values of Young's modulus ranging from 0.5 to 3 Pa. the membranes were then coated with a layer of silica nanoparticles saturated with fluoroalkyl silane to achieve a static contact angle larger than 155° and sliding angle smaller than 5°. Each membrane was mounted on an accurate ring holder with possible adjustable pre-tensioning. A high-sensitive piezoelectric force probe with measuring range of 0-10 N and accuracy of 0.001 N was connected below the holder to record the impact force and its temporal growth.



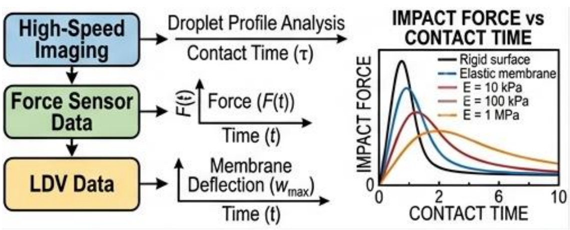
Section A



Section B



Section C



Section D

Fig. (1) An overview of the experimental setup (section A), the fabricated cross-section device structure (section B) proposed in this work, membrane properties and mechanism (section C), and measurement and data analysis (section D)

The droplet production system was constructed from an accurate injection pump supplied with a standard needle of different internal radii (0.2-0.8 mm) to produce droplets from distilled water and aqueous solutions with different surface concentrations and volumes ranging from 2 to 20 mL and the impact velocity was adjusted by varying the falling height from 5 to 50 cm to cover the Reynolds and Weber numbers in the ranges of 500-5000 and 10-200, respectively. An ultrafast Photron FASTCAM SA-Z camera with frame rate of $5x10^4$ frame/s and spatial accuracy of 1024x1024 pixels was used. This camera was mounted on the horizontal axis with background lighting from high-frequency LEDs to record the impact stages starting from the first contact, through the maximum diffusion, starting shrinkage, and finally the complete retraction or dispersion if possible. Beside, another camera was mounted on the vertical axis to observe the symmetry of droplet diffusion and membrane distortion using a special image processing software to extract the dynamic parameters such as maximum diffusion diameter, dynamic contact angle, total contact time, and post-retraction membrane vibration amplitude.

The experiments were carried out at temperature of 25±1 °C and humidity of 50±5%. Each experiment was repeated five times to guarantee the statistical reproducibility and the data were recorded digitally and analyzed using MATLAB software to predict the relationships between the characteristics of the flexible membranes and impact parameters to prepare for comparison with the theoretical models proposed in the literature.

3. Results and Discussion

Figure (1) shows the curves extracted from the relationship between impact velocity (V_0) and contact time (τ) for the superhydrophobic flexible membranes. It is observed that the contact time at low velocities (up to 0.5 m/s) is about 9.5 ms, which refers to the dominance of the flexible behavior of the membrane in dissipating the energy without observable change in time. As the velocity is increased, the contact time starts to gradually decrease to reach 6.8 ms at velocity of 2.5 m/s and then vanishes to zero at velocity of 2.6 m/s, which may refer to complete scattering of the droplet or losing contact. This nonlinear decrease reveals the role of flexibility in accelerating the retraction process as well as reducing the contact time when compared to solid surfaces in accordance to the mechanisms of kinetic energy transformation into vibrational energy in the membrane [27,28].

Figure (2) summarizes the featured dynamics of droplet impact on the superhydrophobic flexible membranes compared to the solid membranes. The scheme (3A) explains the sequential stages starting from the maximum diffusion and ending by list-off, with highlighting the moment of the maximum deviation of the membrane as the stored elastic energy (U_{el}) reaches its maximum while the droplet momentum (p_{drop}) is at the minimum levels. After that, the retraction stage converts the elasticity energy into vertical momentum (p_z) to push the droplet to lift-off just like the launch jump. Scheme (3B) and figure (3C) present a comparison between the flexible and solid behaviors throughout the natural variation of substrate deviation and droplet vertical momentum as functions of normalized time. It is apparently observed that the flexible membrane achieves the highest momentum at the lift-off moment when compared to solid membrane. This confirms the role of membrane's flexibility to enhance the retraction process via energy storage and effectively release, which – in turn – explains the reduction in total contact time and increase in retraction efficiency in the practical applications [29,30].

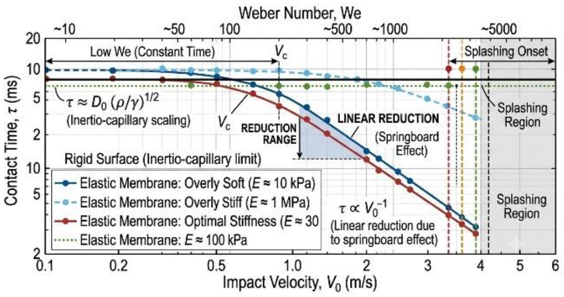


Fig. (1) Droplet contact time vs. impact parameters

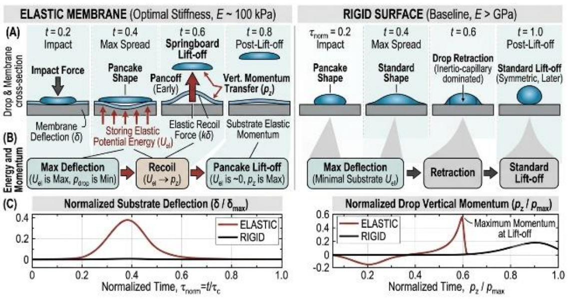


Fig. (2) Schematic explanation of the mechanism of membrane elasticity and drop dynamics during springboard lift-off

4. Conclusion

In concluding remarks, the flexibility of the superhydrophobic membrane plays pivotal role in enhancing the dynamics of droplet impact as it provides a mechanism of elastic energy storage during the stage of maximum deviation and then energy launch as a vertical momentum supporting the lift-off process and reducing observably the contact time when compared to the solid surfaces. Results also showed a nonlinear relationship between impact velocity and contact time with a constant behavior at low velocities and transformation to sharp scattering at high velocities. These observations propose a strong base to develop smart flexible surfaces for anti-freeze and water collection applications.

References

[1] H. Naeim, F. Mahdavian, and D. Rodrigue, "Review on electrospinning of recycled polymer-derived fibers: A road towards sustainability, production and applications", *J. Enviro. Chem. Eng.*, 13(6) (2025) 119283.

[2] Z. Hu et al., "Energy harvesting of droplet-based triboelectric nanogenerators: From mechanisms toward performance optimizations", *DeCarbon*, 5 (2024) 100053.

[3] J.J. Ji et al., "AI-Enabled Flexible Sensing Skin for Next-Generation Aircraft: Toward Embodied Intelligence", *Research*, 9 (2026).

[4] D. Lang et al., "Anisotropic waste PVC/Cotton stalk cellulose composite sponges with under-oil superhydrophobicity for efficient oil-water separation", *Separat. Purif. Technol.*, 373 (2025) 133575.

[5] Z. Fu et al., "Wood elasticity and compressible wood-based materials: Functional design and applications", *Prog. Mater. Sci.*, 147 (2025) 101354.

[6] B.S. Yilbas et al., "Dynamics of ferro fluid droplet impact on hydrophobic mesh surface", *RSC Adv.*, 15(33) (2025) 27167-27176.

[7] E. Arzt et al., "Functional surface microstructures inspired by nature – From adhesion and wetting principles to sustainable new devices", *Prog. Mater. Sci.*, 120 (2021) 100823.

[8] R. Agarwal and A. Mohamad, "Gallium-based liquid metals as smart responsive materials: Morphological forms and stimuli characterization", *Adv. Colloid Interface Sci.*, 329 (2024) 103183.

[9] H. Li et al., "Biomedical applications of nanoparticles made by flame spray pyrolysis", *Prog. Energy Combus. Sci.*, 113 (2026) 101272.

[10] K.R. Hossain et al., "Hexagonal network cat paw-inspired iongel composites improve tribological properties", *J. Ionic Liquids*, 5(2) (2025) 100173.

[11] F. Núñez-Gálvez et al., "Water-resistant hybrid perovskite solar cell - drop triboelectric energy harvester", *Nano Energy*, 148 (2026) 111678.

[12] Y. Huang et al., "Enhancing separation of oil-in-water slop oil via chemical-assisted centrifugation: Toward scalable and energy-efficient treatment of oil sands waste", *J. Hazard. Mater.*, 501 (2026) 140935.

[13] D. Muringaniza et al., "Recent progress in synthesis and applications of monolithic metal–organic frameworks", *Mater. Adv.*, 7(1) (2025) 40-82.

[14] S.K. Ghadei, K.J. Sankaran, and R. Sakthivel, "Hybrid nano-interfacial engineering of special-wettable surfaces for advanced oil/water separation: Multifunctional strategies and future directions", *Result. Surf. Interfaces*, 19 (2025) 100526.

[15] N. Rabiei and M.H. Kish, "Alkaline hydrolysis of polyethylene terephthalate (PET) textiles − A review", *Mater. Today Commun.*, 54 (2026) 115700.

[16] D. Marra et al., "Migration of surface-associated microbial communities in spaceflight habitats", *Biofilm*, 5 (2023) 100109.

[17] H. Lee et al., "Recent progress in the development of porous polymeric materials for oil ad/absorption application", *RSC Appl. Polym.*, 3(1) (2024) 43-77.

[18] S. Priya et al., "Bioinspired nanostructured surfaces for antimicrobial and antifouling applications", *Colloid Interface Sci. Commun.*, 70 (2026) 100863.

[19] M. Rayhani and C. Jian, "A review of molecular dynamic simulation on polymer electrolyte membrane fuel cell", *J. Power Sour.*, 657 (2025) 238143.

[20] F. Topuz and T. Uyar, "Electrospinning of sustainable polymers from biomass for active food packaging", *Sustain. Food Technol.*, 2(5) (2024) 1266-1296.

[21] H. Han et al., "Triboelectric nanogenerators for mechanical energy harvesting: principles, structures and applications", *Energy Conver. Manage.: X*, 30 (2026) 101700.

[22] Z. Wang et al., "Dynamic interfacial vortex arrays for advanced antifouling", *Cell Rep. Phys. Sci.*, 6(8) (2025) 102727.

[23] J. Zhang et al., "Addressing bacterial threats in a post-antibiotic era: Bioinspired strategies for antibacterial surface design", *Adv. Bionics*, 1(2-3) (2025) 92-112.

[24] Y. Sun et al., "Liquid marbles, floating droplets: preparations, properties, operations and applications", *RSC Adv.*, 12(24) (2022) 15296-15315.

[25] W. Bo et al., "Advances in superhydrophobic material research: from preparation to electrified railway protection", *RSC Adv.*, 14(17) (2024) 12204-12217.

[26] L. Deng and L. Liu, "Perception, physiological mechanisms and biological protection strategies against frost stress in orchard systems: A review and future perspectives", *Plant Stress*, 21 (2026) 101427.

[27] O.A. Hammadi, M.K. Khalaf and F.J. Kadhim, "Effect of Adding Nitrogen to the Gas Mixture on Plasma Characteristics of a Closed Field Unbalanced DC Magnetron Sputtering System", *Iraqi J. Appl. Phys.*, 10(1) (2014) 27-31.

[28] H. He and Z. Guo, "Superhydrophobic materials used for anti-icing Theory, application, and development", *iScience*, 24(11) (2021) 103357.

[29] B.D. Cardoso et al., "Tunable physicochemical properties of PDMS@nanoparticle composites: modifications, mechanisms, and emerging applications", *Prog. Mater. Sci.*, 159 (2026) 101656.

[30] J. Liu et al., "Design and development of coating for metallic bipolar plates in proton exchange membrane fuel cell (PEMFC): A review", *Mater. Design*, 246 (2024) 113338.

[31] S. Yao et al., "Anti-fouling coatings for blood-contacting devices", *Smart Mater. Med.*, 5(1) (2024) 166-180.

