Experimental investigations on bio-inspired surface coatings for aircraft icing mitigation

Liqun Ma
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/etd
Part of the Aerospace Engineering Commons

Recommended Citation
Ma, Liqun, "Experimental investigations on bio-inspired surface coatings for aircraft icing mitigation" (2019). Graduate Theses and Dissertations. 17053.
https://lib.dr.iastate.edu/etd/17053

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
Experimental investigations on bio-inspired surface coatings for aircraft icing mitigation

by

Liqun Ma

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Aerospace Engineering

Program of Study Committee:
Hui Hu, Major Professor
Alric Rothmayer
Ashraf Bastawros
Chunhui Xiang
James Michael
Jin Tian

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa

2019

Copyright © Liqun Ma, 2019. All rights reserved.
# TABLE OF CONTENTS

| LIST OF FIGURES | .................................................................................................................. iv |
| LIST OF TABLES | .................................................................................................................. viii |
| ACKNOWLEDGMENTS | ............................................................................................................... ix |
| ABSTRACT | .................................................................................................................. x |

## CHAPTER 1 GENERAL INTRODUCTION ....................................................... 1
  1.1 Literature Review ................................................................................. 1
  1.2 Motivation of Current Research .......................................................... 11
  1.3 Outline of the Dissertation .................................................................. 12
  References ................................................................................................ 13

## CHAPTER 2 AN EXPERIMENTAL STUDY ON THE DYNAMICS OF WATER DROPLET IMPINGEMENT ONTO BIO-INSPIRED SURFACES WITH DIFFERENT WETTABILITIES ......................................................... 19
  Abstract .................................................................................................. 19
  2.1 Introduction .......................................................................................... 20
  2.2 Experimental Method .......................................................................... 23
  2.3 Results and Discussion ........................................................................ 29
  2.4 Conclusion ........................................................................................... 43
  References ................................................................................................ 45

## CHAPTER 3 DROPLET IMPACT ON SOFT SURFACES WITH HIGH WEBER NUMBERS ........................................................................ 47
  Abstract .................................................................................................. 47
  3.1 Introduction .......................................................................................... 48
  3.2 Experimental Methods ........................................................................ 51
  3.3 Results and Discussion ........................................................................ 57
  3.4 Conclusion ........................................................................................... 78
  Reference .................................................................................................. 79
CHAPTER 4  AN EXPERIMENTAL STUDY ON THE DURABILITY OF
ICEPHOBIC SLIPPERY LIQUID-INFUSED POROUS SURFACES (SLIPS)
PERTINENT TO AIRCRAFT ANTI-/DE-ICING .................................................. 82

Abstract ............................................................................................................. 82
4.1 Introduction ................................................................................................. 83
4.2 Experimental Methods ................................................................................ 86
4.3 Results and Discussions ............................................................................. 90
4.4 Conclusion ................................................................................................... 104
References .......................................................................................................... 106

CHAPTER 5  AN EXPERIMENTAL INVESTIGATION ON WIND-DRIVEN
DROPLET MOVING ON SURFACES WITH DIFFERENT WETTABILITIES ....... 109

Abstract ............................................................................................................. 109
5.1 Introduction ................................................................................................. 109
5.2 Experimental Methods ................................................................................ 113
5.3 Force Balance Analysis ............................................................................... 116
5.4 Results and Discussions ............................................................................. 123
5.5 Conclusion ................................................................................................... 130
References .......................................................................................................... 130

CHAPTER 6  AN EXPERIMENTAL INVESTIGATION OF A WIND-
DRIVEN WATER DROPLET OVER THE SLIPPERY LIQUID INFUSED
POROUS SURFACE .......................................................................................... 133

Abstract ............................................................................................................. 133
6.1 Introduction ................................................................................................. 134
6.2 Experimental Methods ................................................................................ 137
6.3 Results and Discussions ............................................................................. 145
6.4 Conclusion ................................................................................................... 152
References .......................................................................................................... 152

CHAPTER 7  GENERAL CONCLUSION ............................................................... 155
7.1 Major Accomplishments of the Current Research ..................................... 155
7.2 Recommendations for Future Research .................................................... 156
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Schematic of the experimental setup for droplet impingement measurements.</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Comparison of different wind tunnel designs to accelerate an individual droplet</td>
<td>25</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>The dimension of the goose feather sample.</td>
<td>26</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Parameter space</td>
<td>27</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Comparison of contact angles on different surfaces.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Evolution of droplet impingement on different surfaces with Weber numbers around 1800.</td>
<td>31</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Evolution of wetting area diameter during the droplet impingement on different surfaces with Weber numbers around 2200.</td>
<td>33</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Evolution of droplet impingement on the hydrophilic surface at different Weber numbers</td>
<td>34</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>Evolution of droplet impingement on the goose feather at different Weber numbers</td>
<td>35</td>
</tr>
<tr>
<td>Figure 2.10</td>
<td>Evolution of droplet impingement on the SLIPS at different Weber numbers</td>
<td>37</td>
</tr>
<tr>
<td>Figure 2.11</td>
<td>Evolution of droplet impingement on the superhydrophobic surface at different Weber numbers</td>
<td>38</td>
</tr>
<tr>
<td>Figure 2.12</td>
<td>Detailed views of the droplet impingement on the goose feather when the Weber number is 3250.</td>
<td>41</td>
</tr>
<tr>
<td>Figure 2.13</td>
<td>Schematic mechanism of high-speed droplet impingement on different surfaces</td>
<td>43</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>A schematic of the experimental setup</td>
<td>52</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Experimental setup for the ice adhesion strength measurement.</td>
<td>54</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Ice adhesion strength as a function of the shear modulus when the surface thickness is 200 μm.</td>
<td>55</td>
</tr>
</tbody>
</table>
Figure 3.4. Different impact dynamics on the aluminum surface and soft PDMS gel surface........................................................................................................57

Figure 3.5. Phase diagram of water droplets impinging on a soft surface as a function of t-PDMS concentration and Weber number........................................59

Figure 3.6. Comparison of droplet impact dynamics on surfaces with different shear modulus when the Weber number is 900. ..................................................61

Figure 3.7. Comparison of the normalized contact diameter evolution on different surfaces when the Weber number is 900 ..........................................................61

Figure 3.8. Comparison of droplet impact dynamics on surfaces with different shear modulus when the Weber number is close to 2700.........................................62

Figure 3.9. Evolution of the droplet impact process when the water film breaks from the center to the edge. .......................................................................................64

Figure 3.10. Evolution of the droplet impact process when the water film breaks from the edge to the center. ...............................................................66

Figure 3.11. Normalized maximum contact diameter as a function of Weber number ..................................................................................................................67

Figure 3.12. Differences in surface deformation for droplet impingement with different impact dynamics .................................................................70

Figure 3.13. Surface deformation function δ(r) for different surface stiffness k and impact velocity $U_0$. ................................................................................74

Figure 3.14. Distribution of $U_0^{1.56}/k$ with the phase diagram overlapped ..........75

Figure 3.15. Ice accretion process over the suction-side surfaces of NACA 0012 test model where AoA = 5.0 °, $U_\infty = 40$ m/s, LWC = 1.0 g / m$^3$, and $T_\infty = -5$ °C..................................................................................................................76

Figure 3.16. Ice accretion process over the pressure-side surfaces of NACA 0012 test model where AoA = 5.0 °, $U_\infty = 40$ m/s, LWC = 1.0 g / m$^3$, and $T_\infty = -5$ °C. ..................................................................................................................77

Figure 4.1. Schematic of the experimental setup for the spray generator ..................86

Figure 4.2. Spray property measured by PIV. ..........................................................88
Figure 4.3. Comparison of dynamic ice accretion process over different surfaces on the DU96-W-180 airfoil under the glaze icing conditions. ........................................... 91

Figure 4.4. Comparison of water droplet impacts dynamics onto different surfaces. ...... 92

Figure 4.5. The initial stage of the water spray erosion on the SHS and the SLIPS when the $U_\infty$ is 45 m/s, LWC is 22 g/m$^3$. ................................................................. 93

Figure 4.6. AFM scanned surface topology images of SHS with the spray impact velocity of 65m/s. ........................................................................................................ 95

Figure 4.7. CLSM scanned surface topology images of SLIPS with the spray impact velocity of 75m/s. ........................................................................................................ 96

Figure 4.8. Hysteresis variation as a function of count of droplet impingement on the SHS and SLIPS. ............................................................................................................ 99

Figure 4.9. The damage-cycle relationship for the SHS and the SLIPS. ...................... 100

Figure 4.10. Comparison of a wettability-based lifetime for the SHS and the SLIPS regarding spray speed. ........................................................................................................ 101

Figure 4.11. Typical surface damage styles for the SLIPS under water spray erosion. (wind speed is 75 m/s) ....................................................................................... 102

Figure 4.12. Mechanism of surface degradation by spray erosion for the SHS and the SLIPS .................................................................................................................. 103

Figure 5.1. Schematic experimental setup for PIV measurement .................................. 113

Figure 5.2. Side view of a wind-driven droplet ................................................................. 116

Figure 5.3. Control volume for the wind-driven droplet. ............................................. 118

Figure 5.4. Comparison of the estimated projected droplet profile (red curve) and the raw image during droplet motion on the PDMS surface. ....................... 122

Figure 5.5. PIV measurement results for the wind-driven droplet movement on the PDMS surface ............................................................................................................. 123

Figure 5.6. Droplet advancing and receding point positions and freestream wind speed variation on the PDMS surface (droplet volumes is 40μL). .......................... 124

Figure 5.7. Comparison of velocity profile in front of the droplet on the SHS surface with droplet volume equal to 5 μL ................................................................. 126
Figure 5.8. Comparison of drag force variation between experimental and theoretical results. .......................................................... 127

Figure 5.9. Force balance on 50μL droplet on different surfaces ........................................ 127

Figure 5.10. Prediction of critical wind speed ............................................................................ 128

Figure 5.11. Effect of boundary layer thickness ........................................................................... 129

Figure 6.1. Schematic experimental setup for PIV measurement ................................................. 137

Figure 6.2. The viscosity of aqueous glycerol solutions under different temperatures. (Segur 1953) .................................................................................................................. 139

Figure 6.3. The 2D geometry of the droplet with particles illuminated in the x-y plane. .......................................................................................................................... 141

Figure 6.4. The image correction for optical distortion ................................................................. 143

Figure 6.5. Displacement of the droplet contact points and the wind speed. ......................... 145

Figure 6.6. Variation of contact angle on SLIPS ......................................................................... 145

Figure 6.7. Variation of droplet moving speed with changing wind speed for different droplet viscosities (percentage of water in %). ........................................... 146

Figure 6.8. Variation of droplet moving speed with changing droplet viscosities. ....... 147

Figure 6.9. Time averaged velocity field inside and outside of the 100% water droplet. The contour of the velocity magnitude with velocity vector fields overlapped. ........................................................................................................ 148

Figure 6.10. Time averaged horizontal velocity profiles near the droplet. ............................ 149

Figure 6.11. Time averaged velocity field inside the 20 μL droplet when the wind speed is 3.9 m/s ............................................................................................................... 150

Figure 6.12. Distribution of the horizontal component of the inner flow field at the vertical line across the circulation center for different droplet viscosities. ........................................................................................................ 151
LIST OF TABLES

Table 2-1. Wettability parameters for different surfaces ........................................... 30
Table 3-1. Measurement of contact angle................................................................. 54
I would like to express my deepest gratitude and appreciation to my major advisor, Dr. Hui Hu, for the precious opportunity of working in his lab in the last three years. Among all the precious qualities I learned from him, diligence and courage to innovation are the most I cherish. Without his generous guidance and support, this dissertation would not have been possible. My whole-heartedly appreciation also goes to my committee members, Dr. Alric Rothmayer, Dr. Ashraf Bastawros, Dr. Chunhui Xiang, Dr. James Michael and Dr. Jin Tian for their insightful comments and suggestions in this work. In particular, I would thank Dr. Jin Tian, my CS minor professor, who enlightened my enthusiasm in artificial intelligence and offered generous help to enable me to envision a challenging future.

I would also extend my appreciations to the staffs of Aerospace Engineering department, especially James Benson, Andrew Jordan, Christine Nelson for their help in the design and machining of the experimental models, and Jacqueline Kester, Sara Goplin, Marisa Mendoza for their help on all the paperwork and many other important things.

Moreover, I am thankful for everyone in Dr. Hu’s research group. I would like to thank Dr. Rye Waldman, Dr. Kai Zhang, Dr. Wenwu Zhou, Dr. Yang Liu, Dr. Haixing Li, Dr. Zhe Ning and Dr. Pavithra Premaratne for their valuable suggestions and helps in completing this research work. I would like to express my sincere gratitude to Mr. Linkai Li and Mr. Hao Guo for their sincere help in both of my work and life. I also want to thank Cem, Prashanth, Linyue, Zichen, A Lusi, Ram, Haiyang, Linchuan, Nianhong and Eric and all my other friends for making my time at Iowa State University a wonderful experience.

Finally, and most importantly, I would express my deepest appreciation to my parents and my grandparents, for their love, confidence, support, and sacrifices on me. This dissertation is dedicated to them.
ABSTRACT

Aircraft icing is widely recognized as a significant hazard to aircraft operations in cold weathers. Bio-inspired water- and ice-phobic coatings are currently being investigated for use as viable strategies for aircraft in-flight icing mitigation. The objective of this study is to evaluate the anti-/de-icing performance of a number of bioinspired hydro-/ice-phobic coatings and explore their potentials for aircraft in-flight icing mitigation.

In the present study, the bioinspired hydro-/ice-phobic coatings examined include the lotus-leaf-inspired super-hydrophobic surface (SHS), the pitcher-plant-inspired slippery liquid-infused porous surface (SLIPS) and the goose-feather-inspired textured surface. Firstly, a comprehensive experimental study was conducted to investigate the dynamics of impacting water droplets onto the test plates with SHS, SLIPS and goose feather surface, in comparison with that of over a conventional hydrophilic aluminum surface. A novel wind tunnel was built to accelerate the droplets to the Weber number up to 3,000, in the range relevant to aircraft in-flight icing phenomena. A high-speed, high-resolution system was used to reveal the droplet impact dynamics at the high Weber number regimes. Secondly, a new anti-/de-icing strategy with icephobic soft materials (e.g., made from PDMS gels) was also explored for aircraft anti-icing applications. The effects of surface stiffness on the dynamics of droplet impingement at high Weber numbers were investigated in great details. The soft surface was also applied to an airfoil/wing model to demonstrate its effectiveness for in-flight icing mitigation in the unique icing research tunnel of Iowa State University (i.e., ISU-IRT). Thirdly, the durability of various surface coatings due to spray erosion pertinent to aircraft icing mitigation scenario was also experimentally investigated and compared for the bio-inspired hydro-/ice-phobic surface
coatings. Surface morphology, wettability, and ice adhesion strength were compared quantitatively after different spray erosion testing durations. A theoretic wettability-based lifetime model was developed following the Cumulative-Fatigue-Damage theory to predict the spray erosion characteristics of the bio-inspired hydro-/ice-phobic surface coatings. Fourthly, the Particle Image Velocimetry (PIV) technique was used to measure the flow fields around the wind-driven droplets on surfaces with various wettabilities. A theoretical model based on the force balance analysis was developed to predict the critical wind speed which dislodges the droplet from the solid surface. Finally, the wind-driven droplet motion on the SLIPS was provided with more details by measuring the flow field inside and outside of the droplet simultaneously using the PIV technique. It showed that the wind-driven droplet internal circulation is related to the droplet viscosity and it will influence the prediction of the droplet moving speed. The findings derived from this study could be beneficial to explore/optimize design paradigms for the development of innovative, low-power anti-/de-icing strategies by leveraging the bio-inspired hydro-/ice-phobic materials/surfaces for aircraft in-flight icing mitigation.
CHAPTER 1
GENERAL INTRODUCTION

1.1 Literature Review

1.1.1 Aircraft Icing and Ice Protection Systems

Aircraft icing is widely recognized as a significant hazard to aircraft operations especially in the cold weather. Green (2006) researched the US in-flight icing accidents and incidents from 1978 to 2005. He observed 645 accidents and incidents occurred using the National Transportation Safety Board (NTSB) online database, and he identified another 299 incidents in NASA Aviation Safety Reporting System (ASRS) reports during the same period. Appiah-Kubi (2013) updated the statistics from NTSB and ASRS, and the databases revealed 228 icing-related accidents and 30 in-flight icing-related incidents from 2006 to 2010. A recent icing accident is a jet crashed into a neighborhood in Gaithersburg, Maryland on Dec. 8th, 2014. According to the NTSB’s report, the probable cause of this accident was the pilot’s conduct of an approach in structural icing conditions without turning on the airplane’s wing and horizontal stabilizer deicing system, which leads to an inevitable aerodynamic stall after the ice accumulation. (National Transportation Safety Board 2016) Until now, aircraft icing remains a significant unsolved problem at the top of the NTSB’s most wanted list of aviation safety improvements.

Aircraft icing is defined as the ice accretion process when supercooled water droplets in cloud impinge and freeze on in-flight aircraft. (Gent, Dart, and Cansdale 2000) Due to low pressure and lack of nucleation nucleus at high altitude, water in the atmosphere does not always freeze even though the temperature is below freezing point. However, the supercooled droplets may turn to ice as an immediate or secondary consequence of contacting with the cold
surface of an aircraft structure. The ice morphology and rate of ice accretion depend on both of the surface conditions (surface finish, material, shape, size, temperature, etc.) and the ambient environmental conditions (airspeed, outside air temperature, liquid water content (LWC), droplet volume median diameter, etc.). (Gent, Dart, and Cansdale 2000) Aircraft icing could be extremely hazardous when the aerodynamic shape has been significantly degraded by the ice built-up which happens within minutes, and it is the significant drag increase and lift decrease that can cause detrimental results.

Rime ice and the glaze ice are the two major types of ice morphology during aircraft icing. In terms of appearance, rime ice looks white and opaque due to the containing of small bubbles and ice grains, while glaze ice appears to be smooth and clear, with water runback icing in aft leading edge regions, and sometimes it has horn-like shapes in front of the leading edge. (Hansman and Kirbyt 1987) Rime ice is formed under a low-temperature and low-LWC condition when the supercooled droplets freeze and accumulate upon impingement. Air could be trapped in between the ice grains, and the ice shape usually follows the airfoil profile. Glaze ice is typically generated with a higher temperature (below freezing point) and larger LWC. Supercooled droplets deform or flow along the surface before freezing, which gives rise to more dramatic ice profiles and larger surface area covered by the ice, and thus glaze ice is often considered to be much more dangerous than rime ice. Mixed ice is generated for conditions in a transition from the glaze ice to the rime ice conditions.

In order to deal with the aircraft icing problems, the icing conditions ahead flight route are estimated from radars or other environmental sensors, therefore flight paths are changed. (Caliskan and Hajiyev 2013) Aircraft also deploys ice protection systems if the icing condition is inevitably encountered during flight. Ice protection systems can be divided into anti-icing
systems and deicing systems according to the differences in ice mitigation strategy. (Thomas, Cassoni, and MacArthur 1996; Fakorede et al. 2016; Goto 2005) Anti-icing systems prevent ice from even forming at the surface of the aircraft, and thus the condensed water collected by airframe surface could be blown away by the upcoming wind. Deicing systems allow ice accretion until it accumulates to an alarming amount, and then they remove the ice layer over the surface via specific mechanisms. Anti-icing systems and deicing systems could be integrated into one system which operates in two modes. (Ibrahim et al. 2015) Typical ice protection systems use techniques such as icephobic coatings (Kim et al. 2012), freezing point depressants (Corsi et al. 2006), pneumatic boots (Bond et al. 1991), electric heater (Giamati 1995), hot bleed air (Saeed 2008), microwave (Salisbury 1997), ultrasonic waves (Palacios et al. 2008), laser (Vega 1988), plasma (Cai et al. 2017), etc. All these techniques could also be divided into passive and active methods in terms of energy consumption. Passive methods do not need energy input to operate while active ones are dependent on the energy of various types.

Passive method is mainly about the application of icephobic coatings which aims at avoidance of water deposition or reduction of ice adhesion strength. Some water repellent surfaces allow water to rebound or roll off the surface before nucleation, which has been demonstrated that they have icephobic properties. (Mishchenko et al. 2010; Cao et al. 2009; Wang et al. 2013) Other icephobic surfaces have low surface energy, which means that the ice adhesion force over these surfaces are so small that the ice could be easily removed. Such surfaces include the polytetrafluoroethylene (PTFE) and the polydimethylsiloxane (PDMS). (Fakorede et al. 2016) Considering its energy efficiency, ice repellent coatings are widely applied in the fields of aviation, wind turbine, and offshore platform.
Active methods could be categorized into three types according to the general mechanisms of ice prevention. The first type is the chemical method. Typical anti-icing and deicing fluids are composed of ethylene glycol (EG), propylene glycol (PG) and other ingredients, and they are usually used for aircraft ground deicing. (“FAA Holdover Time Guidelines Winter 2018-2019” 2018) These chemicals generally depend on pump and spray systems to be applied and some of them could be potentially environmental hazardous considering the considerable amount and frequent applications especially on large commercial airplanes. The second type is the mechanical method. This method generates structural vibration or movement to remove the attached ice. The most commonly used deicing pneumatic boots are mounted on the leading edges of small aircraft wings. They break the ice by successively pulsing inflate and deflate the air chambers, whose deformation could generate bending and shearing stress that can remove ice. Although this method is simple and energy efficient, considerations on installation and maintenance could be huge. The third type is the thermal method. The thermal effect could be generated with hot air, electric heaters, microwave, etc. By maintaining the surface of interest at a temperature above freezing point, ice could not be generated at all. However, the energy consumption grows with the increasing heating area and the decreasing temperature, and sometimes the cost could be expensive.

Passive and active strategies always collaborate to promote ice repellent performance. Particularly, novel hybrid methods could be developed by combining icephobic coatings with the three active methods aforementioned. Sun at al. (2015) developed an anti-icing coating which could secret antifreeze when the surface is subject to ice accumulation and the coating delays onset of glaze formation ten times longer than surfaces flooded with a thin film of antifreeze. In an early study by Bowden (1956), coating with low ice adhesion force was
applied on the pneumatic boots and it was found that ice shedding performance could be considerably promoted with icephobic coatings. Antonini at al. (2011) uses water repellent coatings for the electrical heaters equipped on a wing with NACA 0021 airfoil. They demonstrated that surface wettability is an important controlling factor not only for reducing ice accretion on the wing but also for reducing by up to 80% the energy required to avoid ice accretion on the wing. With the rapid development of surface engineering, sophisticated surface coatings for aircraft icing mitigation are attracting more and more consideration from aerospace engineers.

1.1.2 Bio-Inspired Ice Mitigation Strategies

People always get inspirations from the mother nature, who provided a vast of solutions to engineering problems through its masterpieces, namely the creatures. Biological surfaces with special wettability are always witnessed in our daily life. Wang at al. (2015) reviewed the bio-inspired surfaces with super-wettability, and typical biological materials mentioned include lotus leaf, rice leaf, butterfly wing, water strider leg, mosquito compound eye, gecko foot, red rose pedal, salvinia leaf, Nepenthes leaf, etc. These surfaces represent multiscale structures, which could generate properties such as low adhesion, superhydrophobicity, self-cleaning, structural color, and drag reduction. Some of these bio-inspired surfaces could be applied to ice mitigation. (Wang et al. 2015)

Lv at al. (2014) reviewed the bio-inspired strategies for anti-icing and the recent progress have been categorized into three aspects. The first strategy is dependent on the timely removal of water droplets by trapping air in the hierarchical surface structures. Typical methods are the applications of artificial superhydrophobic surfaces mimicking lotus leaves. (Jiang et al. 2004) Mishchenko et al. (2010) experimentally show that highly ordered superhydrophobic materials can be designed to remain entirely ice-free due to their ability to
repel impacting water before ice nucleation occurs. However, it was found that superhydrophobic surfaces would have their anti-icing capability influenced by their surface morphology. (Cao et al. 2009) It is also explained theoretically that superhydrophobic surfaces are not always icephobic because the mechanism of water and ice adhesion are different. (Nosonovsky and Hejazi 2012)

The second strategy is to trap liquid to reduce the ice adhesion force after the ice is formed. The trapped liquid could serve as a lubricant, which could substantially reduce the ice adhesion and render it able to shed off under gravity, wind force and vibration. (Lv et al. 2014) The slippery liquid-infused porous surface (SLIPS) is a Nepenthes pitcher plants inspired surface developed by Wong at al. (2011). An extremely low ice adhesion strength of only 15.6±3.6 kPa was achieved for deposited water frozen condition. (Kim et al. 2012) Different from the SLIPS which uses the organic liquid, water itself could also serve as a lubricant layer as long as the liquid phase could be maintained with ice atop. (Rosenberg 2005; J. Chen et al. 2013)

Strategies trapping or introducing other media for anti-icing are classified into the third category. Besides organic and aqueous, the liquid between the substrate and the ice could be antifreeze chemicals, which serves as freezing point depressants when ice is formed on the surface. (Sun et al. 2015) Some of these strategies are inspired by creatures living in subzero environments such as polar fish (DeVries and Wohlschlag 1969), insects (Duman 1977), bacteria (Duman and Olsen 1993) and plants (Griffith and Yaish 2004). The trick is the existence of antifreeze proteins and antifreeze glycoproteins can inhibit ice growth.

It should be noted that there is no unique classification method for bio-inspired ice mitigation strategies. New bio-inspired ice mitigation strategies are still vividly emerging and
some of them are indeed promising. However, some of the bio-inspired ice mitigation strategies tend to be only effective for conditions when the ice is generated from deposited water with static ambient air. In terms of aircraft icing, the icing process is more like a dynamic process which involves lots of parameters such as airspeed, air temperature, LWC, droplet volume median diameter, etc. Whether the newly generated surfaces could be applied to aircraft ice mitigation need further investigations when the aircraft icing conditions were simulated in the laboratory.

1.1.3 Fundamental Physics Problems and Research Methods

Aircraft icing mitigation is an engineering problem involving fundamental physics problems originated from multiple disciplines. In terms of surface coatings, most of the physics problems are related to surface engineering, a sub-discipline from material science, and it is linked to solid mechanics. In terms of aircraft icing, the most active problems rest in aerodynamics and multiphase flow, which are relevant to fluid mechanics. Heat transfer also plays a significant role in governing the icing process over the aircraft. This study majorly considers the fundamental physic problems related to aircraft ice mitigation using bio-inspired surface coatings. This section introduces the common research methods previously used to address these problems.

Surface wettability is the ability of a liquid to maintain contact with a solid surface, and it is controlled by the balance between the intermolecular interactions of the adhesive type (liquid to solid) and the cohesive type (liquid to liquid). (Moldoveanu and David 2016) Wettability is usually evaluated by contact angles. Contact angle (CA) is the angle at which the liquid-vapor (normally air) interface of a droplet meets the solid surface. People usually measure CA by analyzing the droplet shape using a goniometer. Other methods include the
tilting plate method, Wilhelmy plate method, and so on. (Lander et al. 1993) For a static sessile droplet, the static CA $\theta$ is related to interfacial tensions (solid-vapor $\gamma_{sv}$, solid-liquid $\gamma_{sl}$, and liquid-vapor $\gamma_{lv}$) by Young’s equation $\gamma_{lv}\cos \theta = \gamma_{sv} - \gamma_{sl}$. (T. Young 1805) Dynamic CA is defined as advancing CA $\theta_a$ for expanding droplets and receding CA $\theta_r$ for shrinking droplets. $\theta_a$ and $\theta_r$ are usually different and their difference is defined as the contact angle hysteresis $H$. Kowk and Neumann (1999) detailed the measurement of the CA regarding experimental procedures and criteria. Recently, Chen et al. (2018) introduced a smartphone-based instrument for CA measurement and it is matching the performance of a top traditional measurement instrument. It turns out that customer made goniometer could also provide satisfactory CA measurement results.

Ice adhesion strength is an important parameter which could be used to quantify the performance of the icephobic coatings. Work and Lian (2018) reviewed the measurement of ice adhesion to a solid substrate for aircraft icing scenario (impact icing). Measurement methods were divided into three categories as centrifuge test, direct mechanical test (push test and shear test) and miscellaneous tests. They concluded that key parameters affecting ice adhesion strength contain temperature, surface roughness, strain rate, and impact velocity. Previous studies provided limited, even contradicted, trend information about the parameter influence especially when using the impact ice. In general, larger roughness and lower temperature would generate higher ice adhesion force. (Work and Lian 2018) Currently, measurement of ice adhesion force for aircraft icing has not been standardized and the relationship between the ice adhesion and the wettability of a substrate is not clear. Further studies are needed to thoroughly investigate the fundamental physic problems pertinent to ice adhesion strength and impact icing scenarios should be considered for aircraft icing.
Both droplet and ice adhesion forces are closely related to the surface morphology. (Work and Lian 2018; Snoeijer and Andreotti 2013). It is well known that the superhydrophobic surface usually reduces droplet adhesion by promoting a Cassie-Baxter wetting state when multiple length scales are employed for surface morphology. (Shirtcliffe et al. 2004) Performance of liquid infused porous surfaces is highly dependent on the surface morphology of the porous material to maintain a steady liquid film over the solid surface. (Wong et al. 2011) Common measurement methods for surface morphology include optical microscopy, atomic force microscopy (AFM), environmental scanning electron microscopy (ESEM), transmission electron microscopy (TEM) and confocal laser scanning microscopy (CLSM). By using these techniques, recent studies (Paxson and Varanasi 2013; Rykaczewski et al. 2013a; Schellenberger et al. 2015) show that surface morphology measurement could provide quantitative information of the surface geometry in micro or nano scales, which could reveal the underlying mechanisms for coating’s special wettability and low ice adhesion strength.

Durability is another crucial property to evaluate coating performance. Coating durability has been extensively discussed in terms of mechanical durability previously as reviewed by Milionis et al. (2016) Evaluation of durability is dependent of the wearing process and they can be roughly divided as adhesive durability, tangential abrasion durability, liquid bath durability, and dynamic impact durability. (Milionis et al. 2016) For icephobic coatings applied on inflight aircraft, it is the dynamic impact durability that counts for the coating degradation caused by aerodynamic impingement of droplets and crystals inside clouds. In order to simulate the dynamic impact conditions, water spray systems are used to generate droplet impingement (Davis et al. 2014) or to provide the source of ice crystals (Flegel 2017).
Surface wettability, ice adhesion strength, and surface morphology are then measured after different wearing durations to quantify the surface durability. (Malavasi et al. 2014; Jiang et al. 2017) Recent studies show that the icephobic performance typically wears quickly, and the retained icephobicity is not necessarily linked to initial coating performance (Janjua et al. 2017). The durability remains as one of the major prohibitive factors in deploying the innovative bio-inspired icephobic on aircraft.

Besides the coating properties mentioned above, other properties such as surface chemistry and surface mechanical properties also influence the coating performance. Changing of surface chemistry often influences the surface energy between the liquid and solid interface, and thus the CA could be influenced. In order to quantify the chemical composition of the surface materials, common devices were used such as X-ray diffractometer system (XRD) (Robinson and Tweet 1992), energy-dispersive X-ray spectroscopy (EDS) (Goldstein 2003) and Fourier transform infrared spectrophotometer (FTIR) (Smith 2011). Surface stiffness and shear modulus are all mechanical properties of the surface, and they come into play when surface deformation could not be neglected especially during dynamic interactions between the surface and water droplets. Previous study measured these mechanical properties using technologies such as displacement measurement by acoustic sensors under different hydrostatic pressures for water saturated porous solid (Nagy and Blaho 1994), shear modulus measurement with rheometer for soft PDMS gel (Beemer, Wang, and Kota 2016) and PeakForce™ quantitative nanomechanical mapping AFM-based method for high-resolution Young’s modulus measurement of polymers (Young et al. 2011).

Besides researching the surface properties for the bio-inspired icephobic surfaces, the fundamental physics problems root from the interactions between the droplet and the surface.
In this study, such interactions could be generalized into two styles as the droplet/spray impact onto solid surfaces and the wind-driven droplet motion on solid surfaces. In order to simulate the aircraft icing conditions, droplet/spray impact dynamics were investigated after the aerodynamic acceleration was introduced in this study. Using some common methodology mentioned by Yarin at al. (2017), high-speed imaging technique was majorly used to measure the impact dynamics for various icephobic coatings. For the wind-driven droplet motion investigations, the Particle Image Velocimetry (PIV) technique was used to measure the flow field both inside and outside the droplet. With more quantitative flow field details supplied, analysis of force balance for the water droplet could be achieved and a theoretical model could be developed to predict the wind-driven droplet behaviors. These two kinds of liquid-solid interactions are pertinent to the impact icing and water runback icing in aircraft icing scenarios. It is a combination of the droplet-surface interactions and the surface property measurement that established the framework of this study.

1.2 Motivation for the Current Research

Although a lot of novel bio-inspired anti/de-icing coatings were developed during the past decade, whether they can be applied on aircraft icing is still unknown. Based on the previous literature review, in order to suggest a promising icephobic coating for aircraft, at least three questions need to be answered: How to experimentally simulate the aircraft icing condition? How to characterize the coating performance quantitatively? How to predict the icing phenomena using theoretical models? To address these questions, the objectives of the present study are listed as follows:

1. Generate a wind tunnel which accelerates water droplets and investigates the high-speed droplet impact dynamics on the bio-inspired surface coatings.
2. Develop an aerodynamically accelerated spray generator to characterize the durability of the bio-inspired surface coatings quantitatively.

3. Measure the flow details of the wind-driven droplet and establish a theoretical model to predict the wind-driven droplet motions on various bio-inspired surface coatings.

4. Provide advice for the selection of the promising coatings for aircraft ice mitigation.

1.3 Outline of the Dissertation

This dissertation includes seven chapters, and five of them (Chapter 2-5) are in peer-reviewed journal format. Chapter 1 provides a general introduction, and Chapter 7 presents the conclusion.

Chapter 2 presents an experimental study of the dynamics of droplet impingement over bio-inspired surface coating. Impact Weber number reaches up to 3000 in this study by using a novel wind tunnel which can aerodynamically accelerate the droplet. Impact dynamics is compared for the bio-inspired surfaces with different strategies for water repellency.

Chapter 3 introduces the surface stiffness’s effect on droplet impact dynamics. Soft PDMS surfaces with four levels of Young’s modulus are tested for droplet impingement with high Weber numbers. A rebound-splash phenomenon is revealed and the parameter to predict the rebound-splash phenomenon is theoretically derived. The anti-icing performance of the soft surface is also investigated in an icing wind tunnel. Soft PDMS turns out to be a potential candidate for aircraft anti-icing applications.

Chapter 4 compared the durability subject to spray erosion for the aforementioned SHS and SLIPS coatings. In order to simulate the droplet erosion situation for in-flight aircraft, a spray generator is established with the adjustable impact velocity reaching up to 100 m/s. The
surface topology of the damaged surfaces is measured using various microscopic techniques. A wettability-based coating lifetime model is derived according to the Cumulative-Fatigue-Damage theory. The general damage process for the SHS and the SLIPS coatings are concluded.

Chapter 5 investigates the wind-driven droplet with their incipient motion majorly focused. The 2D flow field around the sessile droplet is measured with the PIV technique. The dynamics of the droplet is accomplished by analyzing instantaneous droplet profiles attained by image processing. A theoretical model which take boundary layer theory and Young-Laplace fit into consideration is established to predict the critical wind speed. Influences from the droplet volume and the surface wettability are also discussed in this chapter.

Chapter 6 studies how the internal flow influences the wind-driven droplet movement. Two PIV systems were used simultaneously to measure the flow fields inside and outside of the moving droplet over the SLIPS. The internal flow field distorted by the curved surface has been corrected. We found that the wind-driven droplet could be neither sliding nor rolling over the SLIPS. Instead, the internal circulation promoted by the wind shear could have a different velocity scale compared with the droplet movement, which indicates that the internal flows within the droplet should be considered when constructing the dynamic model.

**References**


Bowden DT. 1956. “Effect of Pneumatic de-Icers and Ice Formations on Aerodynamic Characteristics of an Airfoil.”


High-Resolution Young’s Modulus Measurement of Polymers.” Measurement Science and Technology 22 (12): 125703.
CHAPTER 2
AN EXPERIMENTAL STUDY ON THE DYNAMICS OF WATER DROPLET IMPINGEMENT ONTO BIO-INSPIRED SURFACES WITH DIFFERENT WETTABILITIES

Liqun Ma, Haixing Li, Hui Hu
Department of Aerospace Engineering, Iowa State University, Ames, Iowa, 50011

Abstract
The dynamics of water droplet impingement at high Weber numbers onto bio-inspired surfaces was experimentally investigated. Water droplets with an initial diameter around 3 mm were accelerated to a terminal velocity of 9 m/s inside a newly designed droplet wind tunnel. Comparisons were made between the baseline case of the hydrophilic surface and the three other bio-inspired surfaces, namely the goose feather, the pitcher-plant-inspired slippery liquid-infused porous surface (SLIPS) and the lotus-leaf-inspired superhydrophobic surface. The test cases in this experiment have Weber numbers ranging from $9 \times 10^2$ to $3.4 \times 10^3$ and Reynolds numbers ranging from $1.5 \times 10^4$ to $3.1 \times 10^4$. The process of impingement was recorded using a high-speed digital camera at $10^4$ frames per second. Evolution of the droplet impingement process was presented for different surfaces. The splashing phenomena appeared for all cases in these experiments. From the observed trends, higher Weber numbers lead to shorter impingement periods along with larger maximum spreading diameters. It was observed that the goose feather has a hydrophobic surface with a hierarchical structure. Microscale grooves formed by the barbs on the feather influenced the water film breakup direction during droplet impingement. Droplet impacted on the SLIPS will experience the spreading, receding, rebounding and oscillating stages after the impingement, which will take a relatively longer time to rest in steady compared with other cases. The two-dimensional breakup of the water
film was observed for the goose feather and the superhydrophobic surface. This type of breakup process could start from both the inside and edge of the water film, thus promoting the formation of the secondary droplets. Observations were recorded that high-speed impinging droplets would penetrate the hierarchical structure of the bio-inspired surfaces. Consequently, the local wetting condition was changed from the Cassie-Baxter to the Wenzel state, which is not favorable for hydrophobic or icephobic applications.

2.1 Introduction

Aircraft in-flight icing is widely recognized as a significant hazard to aircraft operations in cold weather. Inflight icing conditions include both the impingement of supercooled droplets onto the aircraft when they fly through the clouds, and impingement of rain and drizzles when aircraft fly through a region with precipitation. Aerodynamic performance of aircraft can be severely deteriorated since less lift and higher drag can be generated when the leading edge lifting surface is covered with ice (Gent et al. 2000). A number of anti-/de-icing systems have been developed for aircraft icing mitigation. Most traditional anti-/de-icing systems rely on heat to evaporate the striking supercooled water. The heat can be provided from the engine bleed air or electrical power (Thomas et al. 1996), which need complicated pipe systems or extra energy supplies. Furthermore, the heat is not always sufficient, leaving water failed to be evaporated run back and freeze at the unheated portion (Broeren et al. 2005). Other anti-/de-icing systems can weep freezing point depressant on the aircraft surface, which can postpone or prevent ice formation by anti-ice chemicals such as glycol based chemicals (Thomas et al. 1996). Besides concerns for the extra payload and the potentially harmful vapors in the cabin, the effectiveness of these chemicals will be decreased after diluted by the impacting droplets, which also leads the ice formation in the downstream surface. Anti-icing strategies capable of
protecting the entire aerodynamic surface, which is also more efficient, economical and environmental-harmless, remained to be developed to fulfill the increasing demand of a safer and more efficient flight of aircraft in cold weather.

With the rapid development of surface science and engineering, some promising bio-inspired anti-icing strategies emerged very recently. Wang et al. (2013) tested the icephobicity of the lotus-leaf-inspired superhydrophobic surface, finding the reduction of water surface contact area can retard the ice nucleation under low humidity. Wong et al. (2011) developed a slippery liquid-infused porous surface (SLIPS) inspired by Nepenthes pitcher plants. By trapping water-immiscible lubricating organic liquid in the surface textures, the “omniphobic” SLIPS turned out to be ice repellent too. Inspired by penguins which lived in the world’s coldest environment, Wang et al. (2016) developed a polyimide nanofiber membrane with novel microstructures imitating the penguin feather. These bioinspired surfaces are promising for hydrophobic or icephobic applications under laboratory conditions. Whether they could be successfully applied to aircraft need more investigations with the test condition comparable to the real world situation.

Given the icing condition for an inflight aircraft, where the supercooled water stays inside the clouds and the inevitable precipitations, birds with large flight height can be the first candidate to help understand how they endure water droplet impingements and avoid ice accretion during flight. Dolbeer (2006) reported the height distribution of birds recorded by collisions with civil aircraft in the United States from 1990 to 2004. It is verified that birds can fly within the height where common clouds with supercooled water exist. Some bird can even reach a height up to 32,000 feet (Dolbeer et al. 2009) which is comparable to the cruise altitude of common commercial aircraft. Srinivasan et al. (2014), Bormashenko et al. (2007) and Liu
et al. (2008) analyzed the hydrophobicity of pigeon and duck feathers. They all concluded that the water repellency of the bird feather is generally attributed to the air cushion in the multi-scale hierarchical texture formed by the barbs, barbules and the nano-sized grooves on the fibers. It should be noted that most of the previous studies on the wettability of feather and other bioinspired surfaces were based on static or low-speed tests. Dynamics of droplet impingement under inflight conditions on these novel bio-inspired surfaces are seldom mentioned. It is indicated that rough surfaces with hierarchical structures can generate very different droplet impinging processes compared with the well-known smooth surfaces (Quéré 2008; Tsai et al. 2011; Kannan and Sivakumar 2008). This paper investigated the high-speed impingement dynamics of water droplets on the bio-inspired surfaces, seeking to provide insights for the application of the novel surfaces for inflight aircrafts.

Droplet needs to be accelerated for tests simulating the inflight situation. Aerodynamic drag will always provide a terminal velocity if droplets are accelerated only by gravity. Dhiman and Chandra (2005) increased the droplet impact velocity by mounting the substrate on the rim of a rotating flywheel, and the collision of a single droplet with the moving substrate was photographed. Visser et al. (2012) achieved high-velocity micro-droplets using the breakup of ultrafast liquid jets generated by laser-induced cavitation. Zhang and Liu (2016) used a vertical wind tunnel to accelerate the droplet. In this study, the droplet was accelerated aerodynamically in a newly designed droplet wind tunnel.

In the present study, an experimental investigation was conducted to examine the dynamics of water droplet impingement onto bio-inspired surfaces with Weber numbers ranging from $9 \times 10^2$ to $3.4 \times 10^3$. Droplet with a mean diameter of 3 mm was accelerated in a newly designed droplet wind tunnel. A high-speed imaging system with a sampling frequency
of $10^4$ Hz was used to record the dynamics of water droplet impact process. The enamel-coated hydrophilic surface, the goose feather, the pitcher-plant-inspired SLIP surface, and the lotus-leaf-inspired superhydrophobic surface were used to compare the impingement dynamics onto surfaces with different wettability. The mechanism of the high Weber number impingement on the test surfaces are interpreted schematically. A better understanding of the water droplets impingement dynamics under high Weber numbers may provide fundamental insight into novel bio-inspired anti-icing strategies for aircraft, which will ensure a safe and efficient flight of aircraft in the future.

2.2 Experimental Method

2.2.1 Experimental Setup

Figure 2.1. Schematic of the experimental setup for droplet impingement measurements.

In order to achieve higher impact velocities, a droplet wind tunnel was designed to accelerate the air surrounding the droplet. As shown in Figure 2.1, a metal ducted fan (JP 70EDF 4s~6s Lipo) was used to suck the diverged then converged flow inside the wind tunnel.
The ducted fan was powered by a constant voltage power supply unit (Volteq HY30100EX), and its rotation speed was controlled by an electronic speed controller (Platinum Pro v3 100A). A 20W LED spotlight provided the background light with a light scattering glass mounted behind the test section. A high-speed camera (PCO tech dimax HS), with a downward perspective of 10°, was positioned in front of the test section. The sampling rate was 10 000 Hz, and at least 1000 frames were recorded for each case. The magnification of the images is 0.045 pix/mm. Water droplets with 3 mm diameters were generated by a syringe mounted over the outlet as shown in Figure 2.1. Free falling droplets from the syringe had a velocity around 4.7 m/s when the tunnel was off. All of the cases were conducted in room temperature.

### 2.2.2 Design of the Droplet Wind Tunnel

A droplet wind tunnel is designed for this experiment to achieve high impact velocities. To ensure a perpendicular impingement onto the test surfaces, a vertical wind tunnel is selected. The droplet can be accelerated by both the gravity and the downward flow. As shown in Figure 2.1, the droplet wind tunnel comprises a contraction section, a test section, and pipe systems to converge the diverged flow to the ducted fan. The contraction ratio is 9 and the test section has an inlet of 3 in × 2 in and two outlets of 1 in × 2 in as their sectional areas. The droplet can be accelerated to 9 m/s before the inflight breakup, which is a result of the process of the drastic aerodynamic acceleration (Pilch and Erdman 1987).

Several design options are considered to make the droplet wind tunnel efficient and economical. Figure 2.2 presents four designs of the wind tunnel test section. Figure 2.2 (a) and (b) have a cylindrical test section which is common for regular wind tunnels. The substrate is mounted with its surface normal to the flow. The flow condition will be critical when the flow speed is high due to unsteady vortex shedding behind the blunt substrates. In addition, if taking
blockage ratio into consideration, larger test section diameter is required for substrates large enough to present the droplet impinging process. More compact and power efficient designs are presented in (c) and (d) of Figure 2.2. The profiles of the test sections follow the streamlines around a finite flat plate and an infinite flat plate, respectively. The test section is bent out around the substrate, which can provide a narrower air passage across the substrate. This experiment has chosen the last design since it will be easier to integrate more sophisticated substrates, like substrates with a cooling system, to the wind tunnel from the bottom.

![Figure 2.2. Comparison of different wind tunnel designs to accelerate an individual droplet](image)

The major concern for the current design is that whether the symmetry of the flow will influence the droplet trajectory significantly. The Stokes number of the droplet was calculated to validate that the droplet is not sensitive to the direction changes of the flow. The Stokes number is defined as the ratio of the characteristic time of a droplet \( t_0 \) to the characteristic time of the flow \( \frac{l_0}{U_0} \). The characteristic time of the droplet is defined as:

\[
t_0 = \frac{\rho D^2}{18 \mu_{\text{air}}},
\]

where the water density \( \rho = 1000 \text{ kg/m}^3 \), droplet diameter \( D = 3 \text{ mm} \) and the air viscosity \( \mu_{\text{air}} = 1.81 \times 10^{-5} \text{ Pa} \cdot \text{s} \), \( t_0 \) is equal to 27.6 s. Using the width of the test section 76.2 mm (3 in) as the characteristic length \( l_0 \) and the highest flow velocity of 50 m/s as the characteristic velocity \( U_0 \), the Stokes number,
in the current experiment is $1.8 \times 10^4$. The large stokes number indicates that the droplet is dominated by its inertia and is not sensitive to the diverged flow direction.

### 2.2.3 Test Surfaces

![Figure 2.3. The dimension of the goose feather sample.](image)

(a) General view of a water droplet placed on the goose feather. (b) Size comparison of the droplet next to a quarter over the goose feather.

Aluminum substrates with a size of 2 in×2 in are used to mount the test surfaces in this experiment. The enamel painted surface is used to observe the impingement dynamics onto the hydrophilic surface, which is regarded as a comparison baseline in this experiment. Three bio-inspired surfaces are tested for comparison, namely the goose feather, the pitcher-plant-inspired SLIP surface (Wang et al. 2013) and the lotus-leaf-inspired superhydrophobic surface. Specimens of the feathers were natural goose feathers gathered from the field. The feathers were immersed in a 91% Isopropyl alcohol solution for 60 min at room temperature and then dried at the room temperature for more than 5 hours. Feathers with larger areas were selected so that the specimen with a suitable size can be cut down to fit on the substrate. The substrate can only be partially covered since the feather’s size is confined by the original feather and the removed rachis. Figure 2.3(a) presents the view of a droplet placed on the goose feather and Figure 2.3(b) shows a droplet with its diameter close to the test conditions. The grooves
between the barbs and the tiny furry fabric from the barbules in between the grooves can be observed from Figure 2.3(a). It is believed that this hierarchical structure contributes to the hydrophobicity of the bird feather. (Quéré 2008; Tsai et al. 2011; Kannan and Sivakumar 2008) The SLIPS is provided by Professor Tak-Sing Wong at Pennsylvania State University. It is used as a reference to investigate the influence of oil or grease. The superhydrophobic surface is achieved by applying the substrate with the Hydrobead® Standard coating. Compared with the feather surface with branch-like structures, water droplet cannot penetrate the hierarchical structures thoroughly for this superhydrophobic surface.

### 2.2.4 Parameter Space

![Parameter Space Diagram](image)

**Figure 2.4. Parameter space**

(a) Weber numbers vs. droplet impact velocities and (b) Ohnesorge number vs. Reynolds numbers.

Besides the surface wettability, the dynamic process of droplet impinging onto solid surfaces is majorly determined by surface tension, viscosity, and inertia of the water droplet. Figure 2.4 presents the phase diagram of the test parameters during this experiment. Figure 2.4
(a) shows the relation between the Weber number and the impact velocity. The Weber number is defined as:

\[
We = \frac{\rho U_{\text{impact}}^2}{\sigma},
\]

(2.3)

where \( \rho \) is the water density and \( \sigma \) is the water surface tension. For each kind of substrate, 7 cases are conducted with impact velocities changing from 4.5 to 9.0 m/s, yielding a series of Weber numbers ranging from \( 9 \times 10^2 \) to \( 3.4 \times 10^3 \). The droplet diameters were measured by fitting a circle along the edge of the droplet in the first few frames before impingement, while the impact velocities are achieved by calculating the slope of the linear fitting line of the droplet’s lower edge positions. The dashed line in Figure 2.4 (a) presents the relation between \( We \) and \( U_{\text{impact}} \) for the mean droplet diameter from all of the cases. The mean droplet diameter is 3.09 mm, and the corresponding standard deviation from all the cases is 0.083 mm.

Figure 2.4 (b) presents the relation between the Ohnesorge number and Reynolds number. The Reynolds number is defined as:

\[
Re = \frac{\rho U_{\text{impact}}}{\mu},
\]

(2.4)

and the Ohnesorge number is defined as:

\[
Oh = \frac{\mu}{\sqrt{\rho \sigma D}}.
\]

(2.5)

The Ohnesorge number can also be written in terms of \( We \) and \( Re \) as:

\[
Oh = \frac{\sqrt{We}}{Re}.
\]

(2.6)

The current experiment was conducted with Reynolds number changing from \( 1.5 \times 10^4 \) to \( 3.1 \times 10^4 \). The dashed line in Figure 2.4 (b) is presented when \( K = Oh \cdot Re^{1.25} = 57.7 \), which is suggested as a boundary line for deposition and splashing (Mundo at al. 1995) for the droplet
impingement. This experiment has an Ohnesorge number of 0.0019, which means all of the cases should locate at the splashing region.

2.3 Results and Discussion

2.3.1 Wettability of Surfaces

Apparent contact angle (CA) is usually measured to depict the wettability of the feather due to the micro-scale roughness on the contact area. Figure 2.5 presents the sessile droplet profiles on different surfaces tested in this experiment. The cubic spline is used to present the result in Figure 2.5 (a) and the profiles are measured from the sessile droplets which are provided in Figure 2.5 (b). By normalizing each fitting curve with the diameter of the contact area, it is found that the enamel coated surface is hydrophilic since its contact angle is smaller than 90°. The rest three surfaces are hydrophobic. The goose feather surface has a contact angle between the superhydrophobic surface and the SLIPS surface. The specific values for the contact angles are listed in Table 2-1. Note that the two contact angles from left and right for the goose feather are not the same. The contact angle on the right side is larger than the left side one. This difference is because the contact locations regarding the barbs of the feather are different, as shown in Figure 2.5 (b).

![Figure 2.5. Comparison of contact angles on different surfaces.](image)

(a)Fitting curves of the droplet profiles are normalized with the diameter of the contact area; (b) images used to achieve the fitting curves.
Table 2-1. Wettability parameters for different surfaces

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Static CA</th>
<th>Advancing CA</th>
<th>Receding CA</th>
<th>Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrophilic</td>
<td>30-90</td>
<td>70-105</td>
<td>15-60</td>
<td>&lt;90</td>
</tr>
<tr>
<td>Goose Feather</td>
<td>75-145</td>
<td>142-158</td>
<td>70-80</td>
<td>&lt;75</td>
</tr>
<tr>
<td>SLIPS</td>
<td>108-112</td>
<td>105-115</td>
<td>90-105</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Superhydrophobic</td>
<td>155-160</td>
<td>156-163</td>
<td>151-158</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

Table 2-1 presents both of the static CA and the dynamic CA for the four surfaces in this experiment. It is found that the tendency of the hysteresis agrees with the corresponding static CAs, namely the hydrophilic surface has the largest hysteresis and the superhydrophobic surface has the lowest hysteresis. The feather surface also generates some sudden changes when the contact line is moving from one barb to another one. In this experiment, the advancing and receding CAs are measured by capturing the moving contact lines when a droplet is expanding or shrinking. A syringe vertically mounted above the test surface will stick its needle with the droplet during image recording. Thus water can be filled into or sucked away from the droplet without unsteady interferences with the droplet surface. It is observed that the advancing and receding CAs are closely related to the moving speed of the contact line, which is not quantitatively controlled in this experiment. However, changing ranges of the advancing and receding CAs are provided, which can give a glance at the wettability for current test surfaces.
2.3.2 Effect of Surfaces

In order to illustrate the influence from different surfaces, cases with Weber number close to 1800 are selected to present the evolution of the droplet impact process. Names of the surfaces are noted on the top of each column. The time after impingement is noted on the left for each row and the zero instant frame is defined as the last frame before the droplet contacting with the surface. As expected in Figure 2.4, all of the four cases have the splashing phenomena at the early stage of impingement. The spherical shape of the droplets before impingement is

*Figure 2.6. Evolution of droplet impingement on different surfaces with Weber numbers around 1800.*
observed from the first row. The corona phenomena are observed at the instant of 0.7 ms even though there exist noticeable differences for different surfaces.

For the hydrophilic surface, the droplet is spreading with their rim attached to the surface. Tiny substructures are observed in the edge, or the rim before they recede into the spread water film. The droplet will finally deposit on the hydrophilic surface, acting like a water film with the largest diameter it ever reached. The other three surfaces appear to have significant differences for their impact processes. Droplets impacting onto the feather surface and the superhydrophobic surfaces will have their rims partially raised away from the surface during the spreading stage. The water film cannot retain their round edge due to the breakup of the rim started from an early stage. The breakup of the water film also happens in the middle of the water film as individual breakup holes (see the instant of 3.0 ms), which significantly promote the breakup of the water film and lead to the formation of the secondary droplets. These secondary droplets will then rebound or be blown away from the surface by the upcoming wind. More secondary droplets are remained on the feather surface (see the instant of 96.0 ms) compared with the superhydrophobic surface. The droplet impingement process is even more different for the SLIP surface since a longer evolution period with all of the spreading, receding, rebounding and oscillating stages are observed. The last three cases all have a small droplet remained at the site of impingement (see the instant of 96 ms). After removing the remained droplet, it is observed that both the feather and the superhydrophobic surfaces are partially wetted at the impingement location. The SLIPS is more durable to the high-speed impingement of water droplets, which failed to penetrate the surface structures infused by the immiscible oil.
Figure 2.7. Evolution of wetting area diameter during the droplet impingement on different surfaces with Weber numbers around 2200.

Figure 2.7 presents the diameter variation of the wetting area during droplet impingement. The wetting area diameter $D$ is divided by the droplet initial diameter $D_0$ in the y-axis. The dimensionless time $\tau$ is defined as $U_{\text{impact}}/D_0$. The wetting area diameter on the hydrophilic surface will remain the same ($D/D_0 = 5.7$) after reaching the maximum value. The other three surfaces would all have a receding process after spreading. In terms of the maximum wetting diameter, the SLIPS has a similar $D_{\text{max}}/D_0$ value compared with the hydrophilic surface. In comparison, the feather surface has a smaller $D_{\text{max}}/D_0$, and the superhydrophobic surface has a larger $D_{\text{max}}/D_0$. It turns out that the $\tau$ values are almost the same for the four surfaces to reach the $D_{\text{max}}$ value. The superhydrophobic surface could enter a non-wetting state when $\tau < 15$ due to the significant water film breakup process. Both the SLIPS and the feather surface would have a final $D/D_0$ value close to 1 after the droplet impingement. It should be noted that the droplet breakup process leads to a relatively large measurement error, which is very different from the measurement made when the breakup process is missing or the Weber number is low.
2.3.3 Effect of Weber Number

This section focuses on the Weber number’s influence on the evolution of the impingement process. Four Weber numbers were selected to present the results. In a similar fashion as Figure 2.6, Weber numbers are listed on the top of each column and the time after impingement are listed to the left of each row. The background information has been subtracted for Figure 2.8 and Figure 2.10, and large contrast ratio is used to present Figure 2.9 and Figure 2.11.

![Figure 2.8. Evolution of droplet impingement on the hydrophilic surface at different Weber numbers](image)

Figure 2.8 presents the evolution of droplet impingement on the enamel coated hydrophilic surface when the Weber numbers are 900, 1650, 2200 and 3150. A typical corona splashing appeared on this hydrophilic surface. It is then observed that the maximum spreading
diameter is proportional to the Weber number (see instant of 1.6 ms). Larger Weber numbers will generate thinner water film and thinner rims for the crown-like water sheet. As a result, the capillary breakup is promoted, generating more secondary droplets (see instants of 0.8 and 1.6 ms). After the corona splashing, water remaining inside the crown-like water sheet will accrete at the edge of the water film. A temporary thicker rim is observed as shown at 5.0 ms. Water in this thicker rim will gradually regress into the water film. No receding boundary is observed and the water film will remain with its maximum diameter until evaporation.

Figure 2.9. Evolution of droplet impingement on the goose feather at different Weber numbers
Figure 2.9 presents the evolution of droplet impingement on goose surface when the Weber numbers are 900, 1300, 2150 and 3250. In general, the dynamic process of impingement under the selected Weber numbers are similar to each other. Once the droplet reaches the feather, the deformation of the droplet will generate a thin and spreading water film, which will supply less and less water to the expanding water film. As a result, a corona will be generated since the rim cannot retain its shape anymore (see the instant of 0.5 ms). Different from the water film breakup during the formation of the corona, it is observed that the breakup process with a larger scale will appear from the edge region to the center region. The direction of this kind of breakup seems to be related to the direction of the grooves formed by the barbs (see the instant of 1.0 ms for the last columns and the instant of 2 ms for the first two columns). It is also observed that the breakup happens inside the water film (see the instant of 2.0 ms for the second and the fourth columns). However, the breakup started from the edge is much more significant compared to the breakup started inside the water film for the feather surface. The spreading water film is ripped into individual droplets through the breakup processes and the secondary droplet will be then seated on the surface (see the instant of 5.0 ms). Under the current high Weber numbers, the water remaining inside the water film will stick to the feather at the location where the impingement started. This is because the water will penetrate the hierarchical feather structure during the high-speed impingement process, the local wettability has been changed from the Cassie-Baxter state to the Wenzel state.

The major difference caused by the Weber number originates from the timing of the specific stage and the scale of the structures during the impingement process. At the instant of 0.5 ms, the upper half of the droplet still retains its shape for the low Weber number cases while the whole droplet already filled into the water film for the highest Weber number. At the
instant of 3.0 ms, with the increasing Weber number, the area of the remained water film is smaller and smaller due to the aforementioned breakup process.

![Image](image.png)

*Figure 2.10. Evolution of droplet impingement on the SLIPS at different Weber numbers*

Evolution of the droplet impingement on the pitcher-plant-inspired SLIP surface at Weber numbers of 950, 1600, 2200 and 3050 are presented in Figure 2.10. For the first three columns when the Weber number is smaller than 3000, both of the receding (see instants from 2.0 ms to 5.0 ms) and the rebounding (see instants from 20.0 ms to 40.0 ms) processes are observed after the corona splashing. The droplet will rest at the impinging location with an oscillation phenomenon after landing on the surface again. However, when the Weber number is 3050, the rebounding process does not show up. Instead, the breakup process appears inside the water film (see instant of 3.2 ms for the last column), which leads to a circular distribution
of the secondary droplets. In the center, the remaining water film eventually recedes into a droplet, sitting on the impingement location, until being blown away by the surrounding flow. Taking the receding and rebounding process into consideration, droplet impingement processes on the SILPS will take much longer to reach a stable state. The impact dynamics is qualitatively changed when the Weber number is higher. It should be noted that the ability for the SLIPS to retain its local wettability regarding the high-speed impingement is better than the feather surface. That is because the oil layers will be kept sticking to the fabric substrate during the impact process. Thus the droplets impacting onto the SLIPS will not significantly change the local wettability since the oil layer has been maintained. It can be imagined that once the oil layer has been worn out, the impact dynamics will be significantly influenced.

Figure 2.11. Evolution of droplet impingement on the superhydrophobic surface at different Weber numbers
Figure 2.11 presents the evolution of the droplet impingement on the lotus-leaf-inspired superhydrophobic surface when the Weber numbers are 850, 1350, 2300 and 3050. Similar to the feather, the general impingement process including the corona phenomenon at the early impact stage and the breakup process from both the edge and inside the water film, until the initial droplet has broken into multiple smaller secondary droplets. However, several properties are only represented by the superhydrophobic surface. First, the breakup process from the edge of the water film is initiated as holes near the rim, which has no preferable direction compared to the feather surface (see the instant of 1.0 and 1.5 ms). Next, the significance of the breakup process inside the water film is larger than the breakup process starting from the edge (see the instants of 2.5, 3.2 and 3.8 ms). Both the size and the distribution of the secondary droplets produced by the breakup process are more uniform for the superhydrophobic surface (see the instant of 5.0 ms). Finally, there might be some remaining droplets staying on the impact region, but they can gradually roll away driven by the wind from the droplet tunnel. For the current Weber number range, the impingement dynamics on the superhydrophobic surface would not be qualitatively influenced by the Weber number. Cases with higher Weber numbers will require shorter periods to proceed into different stages and have larger maximum spreading diameters for their water films.

2.3.4 Mechanism of Droplet Impingement with High Weber Numbers

Previous sections witnessed that surfaces with different wettability will qualitatively change the dynamics of droplet impingement, and the increased Weber number will squeeze the duration of the impingement process, which allows the droplets to reach a larger expansion with a shorter time. This section generalizes the influences from both the surface wettability and the Weber number, providing an interpretation for the mechanisms of the droplet impingement with high Weber numbers.
Droplet impingement on goose feathers is focused, and detailed views for the evolution of droplet impingement process are provided in Figure 2.12 when the Weber number is 3250. A small contrast value is used in order to illustrate the information beneath the water film. As shown in Figure 2.12 at the instant of 0.5 ms, the thickness difference between the center and the edge region indicates there is an evolution of the water film thickness changing from the center to the edge during the whole impact period. The crown-like water sheet is much thinner at the early stage of impingement. Secondary droplets are generated at the rim region since a critical thickness is reached, and the surface tension will jet them out from the water film as explained by Yarin (2006). The streak shadows appeared on the water film after the instant of 0.5 ms indicates the water film will expand along with the grooved profiles of the barbs. Since the feather barbs will always have some randomly distributed physical or chemical obstacles, the very thin water film will break up once its rim flows above them. It is expected that such obstacle induced breakup will happen on water films with a thickness larger than the critical thickness for a capillary breakup. As noted by the arrows at the instant of 0.8 ms, 1.3 ms, and 1.7 ms, water film flowing over the haphazard obstacles will contribute many enlarging notches to the expanding water film. These notches are favorable to promote the formation of the secondary droplets. The obtrusive obstacles on the barb passing through the impact center seem to be more easily encountered. It is possibly because those obstacles are more sturdy to the forces along the barb’s direction. When the water film becomes thinner and thinner in the center region, capillary breakup appears as holes inside the water film (noted by the arrow at the instant of 2.4 and 2.8 ms). These breakup process will further accelerate the breakup of the water film into more secondary droplets. A unique post impingement phenomenon for the feather surface is that a droplet will penetrate into the surface structure and stick with a very
small CA. On the contrary, the small secondary droplets around it have large CAs. The local wettability change is a result of the transition from the Cassie-Baxter state to the Wenzel state due to water penetration into the feather during the high-speed impingement. Evidence is provided in Figure 2.12 from the instant of 1.3 to 3.5 ms. The water film has a darker appearance at the collision location, which indicates that the air cushion inside the barb grooves has been removed, which will represent different brightness due to the changed refraction property.

![Figure 2.12 Detailed views of the droplet impingement on the goose feather when the Weber number is 3250](image)

The generalized mechanism for the four surfaces is also presented in Figure 2.13. A color gradient is applied to the water droplet and water film, where the darker color indicates a larger thickness. The gray streaks represent the barbs of the feather and the red triangles on
the bars represent the physical or chemical obstacles mentioned in Figure 2.12. A top view of the crown-like water sheet with secondary droplets distributed in the edge is presented in the second column, representing the corona splashing phenomena happened in the early impacting stage. For the superhydrophobic surface, a larger crown-like water sheet with breakup holes at the edge is presented. This indicates that the capillary breakup will happen near the edge of the water film at an early stage, which is because of the thinner edge created by the easier and faster expansion due to its smallest surface hysteresis. These capillary breakup holes will quickly propagate to the rim and then the capillary breakup in the central region appears when the mass of water advects to the edge. These breakup holes with smaller sizes appear to be more uniformly distributed and plays a more significant role to break up the water film for the Superhydrophobic surface. The last phase for the Superhydrophobic surface shows that there exist secondary droplets at the high-speed collision region after the impingement, which might be a result of the undermined local super-hydrophobicity during impingement. High Weber number impingement of droplet on hydrophilic surfaces will leave a water film with the maximum diameter it ever reached during the impact process. After the corona splashing, water moved to the edge will slowly flow back without a receding process. Mechanisms of the high Weber number droplet impingement onto the SLIPS are interpreted with a generalized cartoon in the last row of Figure 2.13. The spreading, receding and rebounding phenomena are presented using arrows. Impingement mechanisms with the highest Weber number for the SLIPS are not illustrated in this schematic since the inner breakup process has similar features with the goose feather and the superhydrophobic surface.
2.4 Conclusion

With curiosity about the water repellent property of bio-inspired surfaces for inflight conditions, an experimental investigation was conducted to study the dynamics of water droplet impingement onto surfaces as the hydrophilic surface, the goose feather, the pitcher-plant-inspired SLIPS, and the lotus-leaf inspired superhydrophobic surface with high impact velocities. Water droplets with diameters around 3.0 mm were accelerated in a newly designed droplet wind tunnel. Weber numbers ranging from $9 \times 10^2$ to $3.4 \times 10^3$ were achieved, and the splashing phenomena appeared in all of the current cases.

The bio-inspired surfaces studied in this experiment have the hydrophobic property. The corona splashing phenomena was observed in the early stage of the impingement. Two kinds of breakup processes appeared which can change the water film into multiple secondary
droplets. The breakup of the water film started from the rim plays a major part for the goose feather surface. The other kind of breakup process started inside the water film was observed on the goose feather, the SLIPS, and the superhydrophobic surface. Within the current range of Weber numbers, higher Weber number will lead to shortened impinging period and larger maximum spreading diameters in general.

Similarities and differences of the impinging process between the test surfaces have been compared. On all of the four surfaces tested in this experiment, droplet impingements are started from the corona flashing phenomena. Tiny secondary droplets were jetted from the rim of the crown-like water sheet. However, the following phenomena can be very different. The water film will remain on the surface with its maximum diameter for the hydrophilic surface. For the goose feather tested in this experiment, it is observed that the remained water film will shrink into a droplet sticking to the feather at the collision location, while the secondary droplets with smaller sizes will rest on the feather surface with a much larger contact angle. The difference between their contact angles is a result of the changed local wettability. More specifically speaking, the High-speed impinging droplet will partially penetrate the hierarchical structure of the feather surface, changing the wetting condition from the Cassie-Baxter state to the Wenzel state, which is not favorable for hydrophobic or icephobic applications. Droplet impacted on the SLIPS will experience the spreading, receding, rebounding and oscillating stages after the impingement, which will take a relatively longer time to rest in steady compared with other cases. While on the superhydrophobic surface, through the two kinds of breakup processes, the water film will break up into several secondary droplets with uniform sizes and finally rebounding away from the surface. It can be imagined
that these surfaces will experience different inflight icing processes since the droplet impingement dynamics are significantly distinguished.

It is suggested that better hydrophobic performance under high Weber numbers can be achieved by integrating the water repellent strategies. For instance, make hierarchical structures on superhydrophobic surfaces to promote the breakup process of the water film, and infuse the multiscale structures with slippery liquid to preserve local wettability. It is also indicated that a theoretical model for the two-dimensional water film breakup is needed to make progress in a better prediction for high-speed liquid droplet impingements.

References


CHAPTER 3
DROPLET IMPACT ON SOFT SURFACES WITH HIGH WEBER NUMBERS

Liqun Ma, Yang Liu, Hui Hu

Department of Aerospace Engineering, Iowa State University, Ames, Iowa, 50011

and

Wei Wang, and Arun Kotta

Department of Mechanical Engineering, Colorado State University, Fort Collins, Colorado, 80523

Abstract

Soft materials have been considered as a potential candidate for durable icephobic surface, which has extremely low ice adhesion strength and high surface elasticity. In this study, we demonstrated the impact physics of the soft surfaces during high-speed impingement of water droplet. Soft surfaces made from PDMS gels with different shear modulus were used to investigate the influence of impact velocity and surface elasticity. With a constant diameter of 3.1 mm, the droplets were accelerated in a vertical wind tunnel with impact velocity ranging from 4.5 m/s to 10.5 m/s. The corresponding Weber number ranges from $9 \times 10^2$ to $4.5 \times 10^3$. Two high-speed cameras were synchronized to record the impact phenomena in both side view and top view. It was observed that the droplets with higher impact velocity would rebound from the elastic soft surface when the surface shear modulus was small. A dramatically large water film was generated in the air which finally broke up into multiple tiny secondary droplets. This newly observed rebound process significantly decreased the maximum contact area during the dynamic interaction between the droplet and the soft surface. Visualizations of detailed impact processes under different Weber numbers and surface shear modulus were presented in this paper. A surface deformation model was developed to predict different impact dynamics. The anti-icing performance of the soft surface was also demonstrated in this paper,
which highlighted the unique benefit of the soft surfaces in switching the dynamic physics of droplet impingement.

### 3.1 Introduction

Strategies to design surface/materials which can withstand environmental challenges have always been attracting researchers in the aerospace community. Nowadays, the development of anti-icing surfaces, or icephobic surfaces, are one of the hottest research topics due to its great potentials for aircraft icing mitigation. (Kreder et al. 2016; Xia and Jiang 2008)

Soft materials are materials that can be deformed or structurally altered by mechanical or thermal stress. Most biological materials are soft, and more and more engineering biomimetic products have introduced soft material to replace the commonly used rigid materials to achieve favorable characteristics. Soft materials can be made both as hydrophobic (Ma and Hill 2006) and icephobic (Lv et al. 2014). Most of the bio-inspired anti-icing materials are soft material. They prevent their surface from icing either use textured or slippery surfaces (Kreder et al. 2016). A recent study demonstrated that ultra-low ice adhesion could be achieved with soft polydimethylsiloxane (PDMS) materials with smooth surfaces (Beemer, Wang, and Kota 2016). It evokes our interests to conduct the present study to evaluate the anti-icing performance and reliability of soft PDMS materials for aircraft inflight icing mitigation, where dynamic impingement of water droplets at high Weber numbers should be taken into consideration.

Dynamics of water droplet impingement onto a surface has been a fundamental topic for fluid mechanics for centuries. For scenario of water droplet impact on solid surfaces, a vast of previous works have been conducted regarding liquid properties (Izbassarov and Muradoglu 2016; Bartolo et al. 2007), surface wettability (Hao et al. 2015; Bird et al. 2013; Xu 2007; Josserand and Thoroddsen 2016) and ambient environmental conditions (Antonini et al. 2013;
Hao and Green 2017). In general, the impact dynamics were majorly characterized by the Reynolds number and the Weber number, defined with the liquid properties as \( \text{Re} = \frac{DV}{\nu} \) and \( \text{We} = \frac{\rho D V^2}{\gamma} \), which balance the inertia with the viscous forces and the capillary forces, respectively. (Gonor and Yakovlev 1977) Most of the previous works consider a relatively small Weber number compared with aircraft inflight condition. Although some studies were conducted to consider the impact dynamics of a water droplet at relatively high Weber numbers (Zhang and Liu 2016; Visser et al. 2012), the target surfaces were always rigid. Alizadeh et al. (2013) and Andreotti et al. (2016) concluded that the mechanical property of the solid surface would also influence the surface wettability. It is because the capillary force and even the surface tension would deform the soft surface, which could generate different impact dynamics due to the changed interfacial conditions. Ma et al. (2017) reported some experimental results about the impact of water droplets onto bio-inspired surfaces at high Weber numbers pertinent to aircraft icing phenomena, however, the softness of the studied surfaces was not well controlled and the textures of the studied surfaces were also not smooth.

Although extensive investigations regarding dynamics of water droplet impingement have been conducted and many fruitful theoretical and empirical models have been established, it is until very recently that studies focusing on drop collisions with soft materials are emerged (Mangili 2010; Chen et al. 2016; Howland et al. 2016). Chen and Bertola (2017) investigated the drop impacting on soft spherical surfaces and the Weber number they tested is ranging from 10 to 200. Chen et al. (2016) investigated the droplet impact on soft viscoelastic surfaces when the Weber number is lower than 200, and they observed partial rebounding of the droplet on the most rigid surface under higher Weber numbers. Howland et al. (2016) concluded that droplet is harder to splash due to the energy loss caused by surface deformation and the Weber
number they tested is lower than 300. High Weber number droplet impingement is always accompanied by splash phenomena and droplet impacting on smooth soft surfaces with Weber number higher than 1000 has not been investigated. To fill that gap, the following facts need to be considered. Firstly, a soft material with controllable low shear modulus needs to be developed. Quantification of the softness is essential when theoretically study this topic. Secondly, a droplet in suitable sizes needs to be accelerated before impingement. To achieve high Weber number impingement, large droplets with high impact velocity, like raindrops (Soto et al. 2014), are more suitable to collide with soft surfaces instead of microdroplets with extremely high velocity considering the erosion effect and the capability of the current image acquisition systems. It is a match between the material and the impingement parameters that can make more progress.

The main objective of the present study is to experimentally investigate the effects of the stiffness of soft PDMS materials on the impact dynamics of water drops at high Weber numbers pertinent to aircraft icing phenomena. During the experiments, both the shear modulus of the soft PDMS surface and the Weber numbers of the impinging droplets were controlled for a comparative study. While the shear modulus of the soft PDMS surface was changed by tuning the recipes to make the PDMS material, the Weber number of the impinging water droplets was altered by adjusting the airflow speed in a vertical wind tunnel. In this study, the Weber number was in the range of 900–3600 and the shear modulus of the soft surfaces were varied from 9–70 kPa. Two high-speed cameras with a sampling rate of 5000 Hz were synchronized to visualize the droplet impact dynamics from both the side view and the top view. We demonstrated that droplet impingement onto the soft surface with higher Weber number could generate a newly observed rebound-splash phenomenon, where an
extensively expanded water film would be generated in the air. A parametric study was conducted to investigate the influence of the shear modulus and the Weber number, respectively. The mechanism of different impact dynamics was explained with a surface deformation model, which turned out to be helpful to predict different impact dynamics. The anti-icing performance of the soft surface was also demonstrated in this paper and the anti-icing mechanism of the soft surface in terms of the droplet impact dynamics was presented.

3.2 Experimental Methods

3.2.1 Experimental Setup for the Droplet Impact Test

Figure 3.1 shows the schematic of the experimental setup used in this study. To achieve high impact velocities, a vertical droplet wind tunnel was designed where the test section locates at the bottom. As shown in Figure 3.1 (a), the droplet wind tunnel included an air conditioner, a droplet generator, a contraction section, a test section, pipe systems, and a metal ducted fan. The contraction ratio was 9 and the test section had an inlet of 3 in ×2 in and two outlets of 1 in×2 in as their sectional areas. A metal ducted fan (JP 70EDF 4s~6s Lipo) was used to suck the firstly diverged then converged flow inside the wind tunnel. The ducted fan was equipped with a constant voltage power supply unit (Volteq HY30100EX), and a rotational speed controller (Platinum Pro v3 100A). Water droplets with diameter 3.1 ± 0.1mm could be accelerated to 9.5 m/s before inflight breakup due to drastic aerodynamic acceleration. As shown in Figure 3.1 (b), the substrate was mounted at the bottom of the test section, subject to the accelerated droplets. Two high-speed cameras (Fastcam Mini WX100, PCO) with two 50 mm macro lenses (50 mm Nikkor 1.8D, Nikon) were synchronized by a pulse generator (Model 565, BNC) to visualize the droplet impact dynamics from both the side view and the top view. The tilted view of the impact dynamics was also used to visualize the general impact dynamics. Two LED spotlights, one under the substrate for the top view illumination and the
other one behind the test section for the side view illumination, were used to provide the shadowgraph of the impact process. The gap between the glass substrate and the bottom acrylic plate was filled by water so that the image of the substrate in the top view is clean. The sampling rate was 5000 Hz and 2000 frames at minimum were recorded for each case.

Figure 3.1. A schematic of the experimental setup

(a) Schematic of the vertical wind tunnel. (b) Schematic of the experimental setup for droplet impingement measurements.

3.2.2 Surface Preparation

In this study, the soft surface with different shear modulus was fabricated from PDMS gels. PDMS is a hydrophobic material which is commercially available, inexpensive and environmentally benign. (Beemer, Wang and Kota, 2016) The PDMS gels were fabricated via hydrosilylation of vinyl-terminated PDMS (v-PDMS) with hydride-terminated PDMS (h-PDMS). The shear modulus was tuned by adding different amounts and different molecular weights of non-reactive trimethyl-terminated PDMS (t-PDMS) to the hydrosilylation mixture. The shear modulus of the PDMS gels monotonically decreased with the increasing concentration of t-PDMS in the hydrosilylation mixture. More detailed information for the
fabrication of the soft surfaces in this paper can be referred to Beemer, Wang and Kota (2016). In this study, the thickness of the PDMS surfaces was \( t = 200 \mu m \). The constant thickness was achieved by tailoring the spin coating speed for the hydrosilylation mixture. The soft surfaces were stick on 2 in \( \times \) 2 in flat glass plates, which were able to be mounted at the bottom of the test section for the droplet wind tunnel. Unless otherwise noted, the softness of the surface is indicated by the t-PDMS concentration, and the 80% concentration of t-PDMS corresponds to the surface with the smallest shear modulus. The shear modulus \( \mu \) of the soft surfaces are 9 kPa (80% t-PDMS), 22 kPa (70% t-PDMS), 40 kPa (70% t-PDMS) and 67 kPa (50% t-PDMS). The Young’s modulus \( k \) of the surfaces is roughly 30 kPa, 80 kPa, 130 kPa, and 180 kPa.

### 3.2.3 Measurement of Surface Wettability

Measurement of contact angle (CA) was conducted using a custom-built apparatus. Measurement of the static contact angles \( \theta_{\text{static}} \) was performed by taking imaged of the sessile deionized water droplet over the test surfaces. The advancing contact angle \( \theta_{\text{adv}} \) and receding contact angle \( \theta_{\text{rec}} \) were measured by expanding and contracting a sessile droplet using a syringe with its needle close to the test surface. The hysteresis \( \Delta \theta \) is defined as the difference between \( \theta_{\text{adv}} \) and \( \theta_{\text{rec}} \). The images were recorded by a high-speed camera (Fastcam Mini WX100, PCO) with a high 12x zoom lens system (LaVision). We randomly selected three different locations on the test surface to measure the contact angles and the averaged value was used as the final results.

As shown in Table 3-1, we compared the wettability of the soft surfaces with the baseline case, aluminum surface. The aluminum surface was hand polished using sand papers with 2000 grit. We used the hydrophilic aluminum surface as the baseline case because of its wide application in aircraft engineering. The receding contact angle of the aluminum surface was too small to measure because the water droplet will stick on its surface and the contact
line would not move when shrinking the droplet by the syringe. As a contrast, the PDMS gels were hydrophobic since their static contact angle is larger than 90°. Considering that the standard deviation of the measurement is comparable to the differences from different cases, it was found that the wettability of the PDMS surface is almost not influenced by the t-PDMS concentration. In other words, the wettability of the PDMS surface could be regarded as independent of the surface shear modulus in this study.

Table 3-1. Measurement of the contact angle

<table>
<thead>
<tr>
<th>Surface</th>
<th>Static CA $\theta_{\text{static}}$ (°)</th>
<th>Advancing CA $\theta_{\text{adv}}$ (°)</th>
<th>Receding CA $\theta_{\text{rec}}$ (°)</th>
<th>Hysteresis $\Delta\theta = \theta_{\text{adv}} - \theta_{\text{rec}}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>26</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50% t-PDMS</td>
<td>110</td>
<td>120</td>
<td>85</td>
<td>35</td>
</tr>
<tr>
<td>60% t-PDMS</td>
<td>110</td>
<td>118</td>
<td>89</td>
<td>29</td>
</tr>
<tr>
<td>70% t-PDMS</td>
<td>106</td>
<td>118</td>
<td>85</td>
<td>33</td>
</tr>
<tr>
<td>80% t-PDMS</td>
<td>111</td>
<td>119</td>
<td>88</td>
<td>31</td>
</tr>
</tbody>
</table>

3.2.4 Measurement of Ice Adhesion Strength

Figure 3.2. Experimental setup for the ice adhesion strength measurement.

(a) Image of the apparatus for the measurement of ice adhesion strength. (b) Schematic of the ice adhesion strength test.

Measurement of ice adhesion strength was conducted through a shear force adhesion strength facility available in the Aerospace Engineering Department of Iowa State University (ISU), which was reported by Beeram at al. (2017). As shown in Figure 3.2(a), a force gauge
(Mark-10, series 4) was mounted over a motorized translation stage, with its probe inserted into an environmental chamber. A cold plate over the Peltier cooler from TETech (CP-061) was embedded in the environmental chamber. Another insulated chamber filled with dry ice was connected to the chamber which helps to flush out the moisture inside the air with subliming CO2 vapors. As shown in Figure 3.2 (b), the cylindrical ice samples with a diameter of 10 mm were frozen on the PDMS gel. A probe connected to the force gauge applied a lateral force to the sample when it was in a linear motion toward the cylinder with a speed of 0.5 mm/s. The tests were conducted with a substrate temperature of -5 °C and -10 °C, respectively.

Five trials were conducted for each condition. As shown in Figure 3.3, the regression analysis indicates that $\tau_{\text{ice}} \propto \mu^{0.5}$, which is in good agreement with the adhesion mechanics given as $\tau_{\text{ice}} \propto \sqrt{W_{\text{adh}}/t} \mu$, as suggested by Kendall and Chaudhury (2007). The lower temperature has a higher ice adhesion strength since the $W_{\text{adh}}$ has increased due to the increased binding force under lower solidification temperature.

![Graph showing ice adhesion strength as a function of the shear modulus with data points for -5 °C and -10 °C.](image)

*Figure 3.3. Ice adhesion strength as a function of the shear modulus when the surface thickness is 200 μm.*
3.2.5 Measurements of Anti-Icing Performance

The anti-icing performance using the soft surfaces were tested in the Icing Research Tunnel available at Aerospace Department of Iowa State University. Detailed information about the Icing research tunnel can be referred to Liu et al. (2017) The 3D printed NACA 0012 airfoil model has a chord length of 152.4 mm and the span length is 406.4 mm. During the anti-icing test, the PDMS gel surfaces with different shear modulus were wrapped around the airfoil surface. The thickness of the PDMS gel was kept the same when testing the droplet impact dynamics. 1/3 of the span was wrapped with the 50% t-PDMS gel; another 1/3 of the span was wrapped with the 80% t-PDMS gel; and the rest of the span was left untreated with the enamel-coated surface. In such a manner, the ice mitigation process on different surfaces could be compared simultaneously. The transient ice accretion process was recorded with a high-speed camera (dimax S4, PCO) with a 50 mm macrolens (50 mm Nikkor 1.8D, Nikon). The camera was positioned normal to the freestream direction of airflow and the pixel resolution is 11.56 pixels/mm.
3.3 Results and Discussion

3.3.1 General Impact Phenomena

Figure 3.4. Different impact dynamics on the aluminum surface and soft PDMS gel surface.

(a) Impingement on the aluminum surface with We = 960. (b) Impingement on 50% t-PDMS surface with We = 960. (c) Impingement on 80% t-PDMS surface with We = 1600. (d) Impingement on 80% t-PDMS surface with We = 2800. Droplet diameters are all 3.1 mm. (a) and (b) has no rebound process, (c) has a partial rebound process, and (d) has a total rebound process.

Figure 3.4 presents the typical droplet impact dynamics on the aluminum surface and soft PDMS gel surface when We is larger than 900. As shown in Figure 3.4 (a), the droplet impacting on the aluminum surface will spread on the surface until the maximum diameter is achieved. Even though water would gradually flow back from the rim to the center, the expanded water film would stay on the aluminum surface with the maximum diameter without receding back to the center. This result agrees with the contact angle measurement, where the receding contact angle could not be achieved. Similar to impact on the aluminum surface, when droplet has relatively small We or the surface has large stiffness, the droplet will horizontally spread on the surface without rebound away from the surface. However, after the droplet reached its maximum diameter, the water film will then recoil back to the center, leading to a
sessile droplet stay on the impact location with a contact angle close to its static contact angle. Secondary droplets might be generated around the main droplet due to the jetted rim of the water film during the impingement.

Figure 3.4 (c) and (d) present the droplet impact process with partial rebound process and the total rebound process, respectively. The partial rebound process is recognized when the rim of the water film could partially rebound away from the surface, while part of the water film will remain on the surface. In Figure 3.4 (c), the whole rim of the droplet is rebound away from the surface and then breaks up with the remained water film in the center. The rim finally breaks up into a ring of multiple secondary droplets blown away by the upcoming wind. The total rebound process is defined as almost all of the droplet will rebound away from the surface. The rebounding rim of the water film has a significant upward vertical velocity component than the partial rebound process. As shown in Figure 3.4 (d), a bowl-like water film was generated in the air and finally broke up into many tiny secondary droplets. These secondary droplets will either rest on the soft surface and the wall of the test section or fly away with the upcoming wind. A big difference has been made on the impact location since the wetting area of the droplet on the PDMS gel has been significantly decreased.

3.3.2 Parametric Studies

3.3.2.1 Phase Diagram

A phase diagram is presented in Figure 3.5 showing whether the droplet impact dynamics has no rebound process, partial rebound process or the total rebound process. PDMS gel surfaces with four different t-PDMS concentrations were used and Weber numbers ranging from 900 to 5000 were tested on each surface. Since the droplet size was kept at 3.1 mm, the corresponding impact velocities range from 4.5 to 10.5 m/s. The rebound-splash phenomena are easier to be generated when the impact Weber number is high and when the surface
modulus is small. The rebound-splash phenomena could not be observed when the Weber number is lower than 1000 if the surface is more rigid than the 50% t-PDMS surface. It indicates that both surface stiffness and the impact Weber number will affect the impact dynamics, and their individual influences will be discussed based on this phase diagram.

Figure 3.5. Phase diagram of water droplets impinging on a soft surface as a function of t-PDMS concentration and Weber number.

(☐ no rebound, ○ partial rebound and ▽ total rebound)

3.3.2.2 Influence of the surface shear modulus

The influence of the surface modulus is compared when the Weber number is fixed at 900 and 2700, respectively. Figure 3.6 presents the top view results for the evolution of the droplet impact process when the Weber number is 900. Droplets did not generate the rebound process at this Weber number. As a comparison baseline, the aluminum surface can be regarded
as a rigid surface. The impact dynamics in the first row is similar to that shown in Figure 3.4(a) since the droplet would remain on the surface with its maximum spreading diameter. As a contrast, droplet impacted on the soft surfaces would have receding phases after the maximum contact area was reached. Water in the droplet will finally concentrate on the impact location. A ring of satellite droplets formed after the spreading process was also observed. The surface deformation of the PDMS gel could be observed using the glare of the LED illumination. The glare in the center of the surface should have uniform brightness when the surface is flat. However, a shadow would be generated if the surface is deformed by the droplet. Dimples at the impact location could be observed in the frames of 0 ms and 1 ms for the PDMS gel surfaces. At the instant of 2 ms, only the dimple on the 80% t-PDMS surface could be observed, indicating the deformation of the surfaces could last longer when the surface modulus is small. The soft surface deformed by the droplet impingement would finally recover to flat due to the damped oscillation, which could be inferred from the decreasing size of the dimple.

Figure 3.7 provides the temporal evolution of the contact diameter for droplets presented in Figure 3.6. The contact diameter is an averaged result measured from 60 evenly distributed directions through the center of the droplet. Droplet impacted on the aluminum surface has the largest maximum contact diameter which will not decrease after spreading. For the PDMS gels, contact diameters will gradually decrease after the droplets have achieved their maximum spreading diameter. Surfaces with larger shear modulus tend to have larger maximum contact diameter for the soft surfaces when the impact Weber number is 900. The slower spreading speed is observed for the 80% t-PDMS surface. It is the surface deformation that dissipated the kinetic energy of the droplet, which makes the spreading process slower in comparison with other surfaces when the surface deformation is relatively small.
Figure 3.6. Comparison of droplet impact dynamics on surfaces with different shear modulus when the Weber number is 900.

Figure 3.7. Comparison of the normalized contact diameter evolution on different surfaces when the Weber number is 900.
Figure 3.8. Comparison of droplet impact dynamics on surfaces with different shear modulus when the Weber number is close to 2700.

Figure 3.8 shows the top viewed evolution of the droplet impact process when the Weber number is close to 2700. According to the phase diagram in Figure 3.5, the rebound process appeared on surfaces when the t-PDMS concentration is 60%, 70%, and 80%. Droplet spread on the aluminum surface achieved a larger maximum contact diameter comparing with the case shown in Figure 3.8. The spreading and the receding process on the surface with 50% t-PDMS concentration have become rather irregular. The receding breakup phenomena were observed and multiple droplets were left on the surface in the final stage. Even though all the rest three surfaces have generated the rebound process, the detailed splash process is very
different. As shown in the case of 60% t-PDMS surface, only part of the spreading rim was rebounded. After the breakup of the water film, there was a large wetting area on the impact location. The wetting area for this case is smaller than the case of 50% t-PDMS surface, which is because some of the water has rebounded away from the surface. The remained water on the surface would finally recede back to the center. For the case of 70% t-PDMS surface, much more water has been rebounded from the surface and the remained wetting area is much smaller. For the softest surface with 80% t-PDMS concentration, almost all of the water inside the droplet has been rebounded from the surface. An extensively expanded water film was generated and finally broke up into multiple tiny secondary droplets. It can be concluded that when the rebound process appears, surfaces with smaller shear modulus tend to have a smaller maximum wetting diameter. It is because more water could be rebounded away from the surface when it has a smaller shear modulus. It is highly indicated that the surface deformation accompanied by the droplet impingement is closely related to the rebound-splash phenomena.

As shown in Figure 3.8 at the instant of 100 ms, the final wetting state for the 70% t-PDMS surface and the 80% t-PDMS surface is very different. The 70% t-PDMS surface is relatively clean and larger droplets are concentrated in the center. However, the 80% t-PDMS surface is densely covered by multiple tiny droplets. We noticed that the breakup direction of the rebound-splashing water film was different. The detailed information is manifested in Figure 3.9 and Figure 3.10, where both top and side views are provided.
Figure 3.9. Evolution of the droplet impact process when the water film breaks from the center to the edge.

The test surface is 70% t-PDMS gel surface and We = 3000 (droplet diameter $D = 3.1$ mm and the impact velocity $U_0 = 8.4$ m/s).

Figure 3.9 presents the droplet impact process with the water film breaking from the center to the edge. After the impingement, the rim of the droplet is rebound away from the surface. As the water film expanded larger and larger, water contacting with the surface could not supply the water film with more liquid, so that the water film becomes thinner and thinner. Water film finally breaks from the contact line between the liquid and the soft surface. The surface tension then drives the breakup from the center to the edge. The secondary droplets
achieved an extra momentum from the surface tension, making them fly away from the center of the impact location. As shown in Fig 9 at the instant of 10 ms, most of the droplets were attached on the wall of the wind tunnel. A smaller droplet remained at the impact location and it was a result of the receded water remained on the surface.

Figure 3.10 presents the droplet impact process where the water film breakup from the edge to the center. The droplet totally rebounds from the surface and the maximum wetting diameter is rather small. Since there are no interferences from the contact line between the droplet and the soft surface, the breakup of the sufficiently expanded water film is initialized from the edge and then propagated to the center. Secondary droplets could be supplied with extra momentum, which follows the direction of the breakup propagation. From the side view of the water film, we know that the breakup propagation direction should have a component facing downward. As a result, the secondary droplets will fly back to the surface, which makes the final wetting state different from that shown in Figure 3.9. However, the breakup of the water film is not initialized from the edge, showing the complexity and the randomness of the breakup process. We conclude that the total rebound process is more easily generated on surfaces with smaller shear modulus. In addition, total rebound process tends to have a final wetting state with multiple tiny droplets around the impact location.
Figure 3.10. Evolution of the droplet impact process when the water film breaks from the edge to the center.

The test surface is 80% t-PDMS gel surface and $We = 2800$ (droplet diameter $D = 3.1 \text{ mm}$ and the impact velocity $U_0 = 8.1 \text{ m/s}$).

3.3.2.3 Influence of the Weber number

Figure 3.11 presents the relation between the normalized maximum contact diameter and the Weber number. We distinguished the cases with the rebound process by using hollowed markers since this phenomenon would significantly influence the distribution of the maximum contact diameter. The results indicate that without the rebound process, higher Weber number
would have larger maximum contact area. The slope of the power fitting lines for different surfaces is close to each other and \( D_{\text{max}} / D_0 \propto \text{We}^{0.2} \). In comparison with the rigid aluminum surface, soft surfaces have smaller maximum contact area. For cases when the rebound-splash phenomena appear, the maximum contact area would be significantly decreased. The maximum contact area will be smaller if the Weber number is higher or the surface modulus is smaller. The maximum contact area can be decreased to the zero for the cases with total rebound process, which was not mentioned in previous studies according to our current knowledge.

*Figure 3.11. Normalized maximum contact diameter as a function of Weber number.*

*RS indicates the corresponding case has the rebound-splash phenomena, which is represented with the solid markers.*
3.3.3  Mechanism

3.3.3.1  Energy balance

Considerations on energy balance have been made to have a better understanding of the interaction between the droplet and the soft surface. We assume that the gravitational potential energy

\[ PE = \frac{\pi}{6} D_0^3 \rho g \frac{D_0}{2} = \frac{1}{12} \pi \rho g D_0^4 \]  

(3.1)

can be neglected during the impingement (less than 0.2% of the kinetic energy), the energy balance on the droplet could be written as

\[ KE_1 + SE_1 = KE_2 + SE_2 + W_{vis} + W_{def} \]  

(3.2)

The kinetic energy before impact is

\[ KE_1 = \left( \frac{1}{2} \rho U_0^2 \right) \left( \frac{\pi}{6} D_0^3 \right) = \frac{1}{12} \pi \rho D_0^3 U_0^2 \]  

(3.3)

and the surface energy of the spherical drop is

\[ SE_1 = \pi D_0^2 \gamma . \]  

(3.4)

The surface energy takes only 1% of \( KE_1 \) at most in this study.

When the surface reached its maximum deformation, the droplet energy has been converted to kinetic energy \( KE_2 \), surface energy \( SE_2 \), energy lost due to viscous dissipation \( W_{vis} \) and surface deformation \( W_{def} \). Although the droplet is stretching by its inertia and the surface deformation, the centroid of the droplet is confined by the surface and thus \( KE_2 \) can be regarded as negligible. The surface energy after impact is

\[ SE_2 = A_{LG} \gamma_{LG} + A_{LS} \gamma_{LS} - A_{LS} \gamma_{SG}, \]  

(3.5)
where \( A \) is the contact area as noted between the liquid, gas and solid. According to Young’s equation

\[
\gamma_{SG} - \gamma_{LS} = \gamma_{LG} \cos \theta_{\text{static}},
\]

the expression of \( SE_2 \) can be written as

\[
SE_2 = \gamma_{LG} (A_{LG} - A_{LS} \cos \theta_{\text{static}}).
\]

\( SE_2 \) should have the same order of \( SE_1 \) since the droplet shape has not drastically changed at this instant and \( A_{LG} - A_{LS} \cos \theta_{\text{static}} \) should be comparable to \( \pi D_0^2 \).

According to Pasandideh-Fard at al. (1996), the expression of the energy lost due to viscous dissipation is:

\[
W_{\text{vis}} = \frac{\pi}{3} \rho U_0^2 D_0 L_{\text{max}}^2 \frac{1}{Re}.
\]

This equation is for the instant when the droplet has spread with its maximum diameter \( L_{\text{max}} \). For the current situation, this equation can be used to estimate the \( W_{\text{vis}} \) by using \( L_{\text{max}} = D_0 \) since the droplet has not significantly spread yet. Results show that \( W_{\text{vis}} \) takes less than 5% of \( KE_1 \) in this study. As a conclusion, most of kinetic energy \( KE_1 \) has been lost in the deformed surface as \( W_{\text{def}} \), which is converted to the surface elastic potential energy \( PE_{\text{surface}} \).
3.3.3.2 Impact dynamics and surface deformation

![Diagram](image)

Figure 3.12. Differences in surface deformation for droplet impingement with different impact dynamics.

(a) Droplet impact without rebound process: before the impact, at the maximal spreading diameter $D_{\text{max}}$ and final state after impact. (b) Droplet impact with partial rebound process: surface with maximal downward deformation, maximal upward deformation and the instant when the rebounding rim breaks up from the water film remained on the surface. (c) Droplet impact with total rebound process: surface with maximal downward deformation, maximal upward deformation and the instant when the water film totally moves away from the surface. Red arrows indicate the possible movement direction of the droplet.

As shown in Figure 3.12, different impact phenomena can be explained by depicting the surface deformation differences during the droplet collision. When the droplet impacts on a rigid surface, as shown in Figure 3.12(a), the droplet will usually spread along the surface horizontally until the maximal diameter is reached. Due to the surface wettability of the PDMS gel, the droplet then recoils to a steady sessile state with a contact angle close to its static contact angle. However, when the droplet impacts on an elastic surface, the surface deformation will influence the direction of the spreading. The rim of the droplet tends to jet
away from the surface when a large deformation is achieved, and this process initializes the
rebound-splash phenomena. To simplify the complicated dynamic process of droplet surface
interaction, we compared the partial rebound and the total rebound process in Figure 3.12(b)
and (c) when the surface reached three typical states with the maximal downward
displacement, the maximal upward displacement, and the recovered zero displacements. The
falling droplet is squeezed by both its inertia and the surface supporting force, yielding to eject
along with the deformed surface. The jetting direction will be more vertical if the deformation
is steeper. The jetting direction for the partial rebound process is less vertical than the total
rebound process, which is also manifested in Figure 3.9 and Figure 3.10. When the surface
oscillates back to its maximal upward displacement, the inertia of the water film is harder to
overcome the surface energy when the surface deformation is small. As a result, the rim of the
water film that already jets away from the surface will break up from the water film remained
on the surface, which leads to the partial rebound phenomena. As a contrast, the whole water
film would rebound away from the surface for the entire rebound process, and the final breakup
of the water film would be initialized wherever the critical instability is reached on the water
film.

3.3.3.3 Model for the surface deformation

The impact dynamics is highly influenced by surface deformation. According to
previous observations and discussions, we use a displacement distribution function $\delta(r)$ to
represent the surface deformation. Previous researchers (Mangili et al. 2012; Chen et al. 2016)
majorly focused on the maximum surface displacement $\delta_{\text{max}}$ during impingement because the
shape influence is not significant when the Weber number is small. For this study, we only
consider the influence from the impact velocity and the surface stiffness, which means all the
other related parameters will be regarded as constants. Considering the deformation
characteristics of the smooth solid surface, we use the Gaussian distribution function to
develop the displacement function. Use an elastic foundation model (EFM) similar to that used
by Mangili et al. (2012), the impact force can be represented as

\[ F = \int_{-\infty}^{\infty} f(r)dr = k \int_{-\infty}^{\infty} \delta(r)dr, \]  

(3.9)

where \( f(r) \) is the force distribution function and we have \( f(r) = k\delta(r) \) due to the linear relation
between the local force and displacement. Use the Gaussian distribution function, we have

\[ \delta(r) = \frac{A}{\sigma} \exp\left(-\frac{r^2}{2\sigma^2}\right), \]  

(3.10)

where \( A \) is a term to be determined and \( r = 0 \) at the center of the impact location.

The shape of the deformation is determined by the standard deviation \( \sigma \), which is a
function of surface stiffness \( k \) and the impact velocity \( U_0 \). When \( k \) is smaller and \( U_0 \) is larger,
the deformation tends to be steeper and thus \( \sigma \) tends to be smaller.

Let \( r = 0 \) we have

\[ \delta_{max} = \frac{A}{\sigma}. \]  

(3.11)

Mangili et al. (2012) analyzed the PDMS substrate deformation after droplet impact when the
stiffness is a constant. The maximum deformation is related to the impact velocity as
approximately \( \delta_{max} \propto U_0^{1.56} \). Although the impact velocity in their study is below 4 m/s, we
assume that their results hold valid for the current model. In addition, use the conclusion that
the surface deformation is inversely proportional to the surface stiffness, we have

\[ \delta_{max} \propto \frac{U_0^{1.56}}{k}. \]  

(3.12)

Now we consider the force distribution
\[ F = \int_{-\infty}^{\infty} 2\pi f(r)dr = \int_{-\infty}^{\infty} 2k\pi \frac{A}{\sigma} \exp\left(-\frac{r^2}{2\sigma^2}\right)dr = 2k\pi A\sigma. \] (3.13)

Note here the integration of the force is not equal to the momentum force mentioned by Mangili at al. (2012) and Soto at al. (2014) due to the surface deformation and viscous dissipation.

The elastic potential energy of the surface \( PE_{\text{surface}} \) is:

\[ PE_{\text{surface}} = \int_{-\infty}^{\infty} \frac{1}{2} k \delta(r)^2 2\pi r dr = \int_{-\infty}^{\infty} \frac{1}{2} k \left(\frac{A}{\sigma} \exp\left(-\frac{r^2}{2\sigma^2}\right)\right)^2 2\pi r dr = \frac{1}{2} k\pi A^2. \] (3.14)

We assume that \( PE_{\text{surface}} \) is proportional to the droplet kinetic energy \( KE_1 \) before the impingement, we have

\[ kA^2 \propto U_0^2. \] (3.15)

As a result,

\[ A \propto \frac{U_0}{\sqrt{k}}. \] (3.16)

Using Eq. 11 and Eq.12, there is

\[ \frac{A}{\sigma} \propto \frac{U_0^{1.56}}{k}. \] (3.17)

We could finally achieve the shape factor \( \sigma \) by combining Eq. 16 and Eq. 17, that is

\[ \sigma \propto \frac{\sqrt{k}}{U_0^{0.56}}. \] (3.18)

Plug Eq. 16 and Eq. 18 back into Eq. 13, we have \( F \propto kU_0^{0.44} \). As a contrast, the momentum force (Soto et al. 2014) follows \( F_{\text{moment}} \propto U_0^2 \). It is indicated that \( F \) is related to both the surface property and the impact velocity, while \( F_{\text{moment}} \) is irrelevant to the surface property.
Considering the contribution from the impact velocity $U_0$, it is reasonable that $F$ is smaller than $F_{\text{moment}}$ since the kinetic energy has been converted to other energy forms.

### 3.3.3.4 Prediction of the rebound process

![Figure 3.13. Surface deformation function $\delta(r)$ for different surface stiffness $k$ and impact velocity $U_0$.](image)

According to the surface deformation function, the predicted surface deformation curves are presented in Figure 3.13 for different surface stiffness and impact velocities. Smaller surface stiffness and larger impact velocity will have larger surface deformations. When $k = 180$ kPa, all the curves are close to the rigid surfaces. However, when $k = 30$ kPa, the valleys of the curves become much deeper and steeper. This result is in good agreement of the tendency shown in the phase diagram in Figure 3.5: no rebound process is found in most of the cases when $k = 180$ kPa and the total rebound cases happen only when $k = 30$ kPa. Deformation
curves with a moderate depth like those when \( k = 130 \text{ kPa} \) and \( 80 \text{ kPa} \) are related to the partial rebound process, which also agrees well with observations.

Figure 3.14. Distribution of \( \frac{U_0^{1.56}}{k} \) with the phase diagram overlapped.

(\( \square \) no rebound, \( \circ \) partial rebound and \( \triangledown \) total rebound)

Figure 3.14 presents the distribution of \( \frac{U_0^{1.56}}{k} \) with the phase diagram overlapped. The boundary between the cases with or without the rebound process has a critical \( \frac{U_0^{1.56}}{k} = 0.2 \) and the boundary between the cases with partial rebound process and total rebound process has a critical \( \frac{U_0^{1.56}}{k} = 0.6 \). Figure 3.14 shows that when the surface stiffness is extremely small, the surface will act as the liquid surface with very large \( \frac{U_0^{1.56}}{k} \). At the same time, the shape factor \( \sigma \) is very small and the surface defamation will close to a spike. This indicates that
the deformation will be not smooth anymore, which agrees with the intuition when imagining a droplet impact on the liquid interface. As the surface stiffness increases, the impact velocity needed to generate the rebound process increases nonlinearly. It is also indicated that when the impact velocity is small, like below 4 m/s in this study, the total rebound process could never appear unless the surface stiffness is below 10 kPa. This result explains why previous researchers could not observe the rebound-splash phenomena on PDMS surfaces without using a droplet accelerating facility.

Not all the cases follow the predicted boundary due to the assumptions we made when deriving the model. For example, the deformation of the PDMS gel layer with a finite thickness is not reversely proportional to the surface stiffness. However, results in Figure 3.14 shows the reasonable capability of predicting the appearance of the rebound process at least in this study. Other parameters like the surface wettability, droplet diameter, ambient pressure, moisture, and temperature need to be considered when further improving the model.

### 3.3.4 Validation with Anti-Icing Performance

![Figure 3.15](image-url)

**Figure 3.15.** Ice accretion process over the suction-side surfaces of NACA 0012 test model where AoA = 5.0 °, $U_∞ = 40$ m/s, LWC = 1.0 g/m$^3$, and $T_∞ = -5$ °C.
Figure 3.16. Ice accretion process over the pressure-side surfaces of NACA 0012 test model where AoA = 5.0 °, $U_\infty = 40$ m/s, $LWC = 1.0$ g/m$^3$, and $T_\infty = -5$ °C.

Ice accretion process over the suction-side and the pressure-side surfaces of the airfoil are presented in Figure 3.15 and Figure 3.16, respectively. The initial ice accretion process is presented for the hydrophilic enamel painted surface and hydrophobic PDMS gel surfaces with a t-PDMS concentration of 50% and 80%. The wind speed $U_\infty$ was 40 m/s with a direction normal to the leading edge (LE) and the trailing edge (TE), and the angle of attack (AoA) was 5.0°. The liquid water content (LWC) was 1.0 g/m$^3$, and the temperature was -5 °C, which simulates a condition where the glaze ice would be generated. Ice was formed on the baseline surface near the leading edge with non-uniform frozen rivulets. However, for the soft surfaces, the leading-edge icing is more uniform and less severe compared to the baseline case. It is rather obvious for the 80% t-PDMS surface on the suction-side since the icing process is hard to be recognized. Ice also distributed on the rest of the airfoil surface for the baseline case due to water runback icing. However, for the soft surfaces, icing due to water runback phenomena was much less dominant and even disappeared for the 80% t-PDMS surface.
Airfoil wrapped with 50% t-PDMS surface has less severe water runback icing than the solid baseline surface is not only because of the difference between their surface wettability. Partial rebound process might have contributed to the much less remained water on the airfoil, which has mitigated the water runback icing. Airfoil wrapped with 80% t-PDMS surface has more uniform ice accretion and no runback ice accretion. The reason is that larger droplets could not remain on the surface due to the whole rebound process. Instead, small secondary droplets will be generated after the impingement, which formed a uniform icing layer and the non-uniform icing due to the formation of rivulet or water runback has been avoided. It is indicated that the soft surfaces have promising anti-icing features under current test conditions.

3.4 Conclusion

In this study, the anti-icing performance of the soft surfaces made from PDMS gels was presented. A comprehensive experimental study was conducted to explore the water droplet impact dynamics on the soft surface. To simulate the in-flight icing condition for aircraft, a vertical wind tunnel was used to accelerate the droplet. The Weber number in this study is one order larger than previous studies tested on soft surfaces. The rebound-splash phenomenon was observed during the experiment. It suggests that the maximum contact diameter could be significantly decreased when the rebound-splash phenomenon appears.

By systematically conducting a parametric study for the impact dynamics, we concluded that without the rebound-splash phenomena, the rigid and the soft surface share the similar tendency: higher Weber number would have larger maximum contact area. However, the softer the surface is, the smaller the maximum contact area would be. When the rebound-splash phenomenon appears, the maximum contact area will become smaller if the Weber number is higher or the surface modulus is smaller.
The mechanism of different impact dynamics was explained with a surface deformation model, which turned out to be helpful to predict different impact dynamics. We found when fixing other parameters as constants, \( U_0^{1.56}/k \) could reasonably depict the surface deformation. In this study, the boundary between no rebound process and partial rebound process is \( U_0^{1.56}/k = 0.2 \), and the boundary for the entire rebound process is \( U_0^{1.56}/k = 0.6 \).

The soft surfaces could effectively prevent the water runback icing in the initial ice accretion stage. We found that under high Weber number, droplet impingement would have much smaller maximum contact area on surfaces with small shear modulus. The surface deformation could rebound the droplet away from the surface, generating an in-air splashing process which allows the upcoming wind to take the resultant tiny secondary droplets away from the surface. However, the corresponding rebound-splash phenomena could not appear if the Weber number is smaller than 1000 when the surface modulus is larger than 9 kPa.

Reference


CHAPTER 4
AN EXPERIMENTAL STUDY ON THE DURABILITY OF ICEPHOBIC SLIPPERY LIQUID-INFUSED POROUS SURFACES (SLIPS) PERTINENT TO AIRCRAFT ANTI-/DE-ICING

Liqun Ma, Zichen Zhang, Linyue Gao, Yang Liu and Hui Hu
Department of Aerospace Engineering, Iowa State University, Ames, Iowa, 50011

Abstract
Recently, bio-inspired surfaces have been found to be hydrophobic and/or icephobic, which has very low adhesion force for water and/or ice. When bio-inspired surfaces are applied for aircraft icing mitigation, they would suffer erosions due to high-speed impacting of the water droplets in the form of fog/mist. However, the knowledge of the coating durability regarding spray erosion is still quite limited. In the present study, an experimental investigation was conducted to evaluate the durability of a PTFE membrane based slippery liquid infused porous surface (SLIPS) subject to water spray erosion, in comparison to that of a commonly used superhydrophobic surface (SHS) coating (i.e., a commercially-available Hydrobead® SHS coating). A wind-driven spray generator was established with the spray erosion speed controllable from 45 m/s to 95 m/s. The anti-icing performance of the SHS and the SLIPS was validated in an icing research wind tunnel. Impact dynamics of individual water droplets at high Weber number about 3,000 and water spray erosion process of the SHS and the SLIPS were compared. The wettability-based coating lifetime was analyzed by measuring the dynamic contact angles on the SHS and the SLIPS under water spray erosions with different velocities. A cumulative-fatigue-damage theory was used to help predict the coating life time for in-flight aircraft icing mitigation. It turns out that the SLIPS could maintain its
hydrophobicity better than the SHS under a moderate spray erosion speed. The mechanism of the spray erosion process for the SHS and the SLIPS was also examined in this study.

### 4.1 Introduction

Ice accretion on inflight aircraft aerodynamic surfaces presents a severe and dangerous risk for aviation security. After the airplane takes off, especially in cold weather regions, it is the super-cooled droplets impingement onto the airfoil surface or engines that majorly lead to the severe icing problems. The icing phenomena on the airfoil or engine will do considerably harm to the aerodynamic performance of the airplane and probably leads to aircraft accident (Liu et al, 2017, 2018). Nowadays, with the rapid development of the surface science and engineering, more and more bio-inspired hydrophobic/icephobic coatings have been designed (Lv et al. 2014) and many of them would have huge potentials to be applied in aircraft anti-icing scenarios.

Superhydrophobic surfaces have contact angles above 150° and they are repellence to water. Wettability is one of the most fundamental properties of solid surface which is governed by the surface chemical composition and the microstructure morphology. The wing of butterfly *Morpho aega* (Feng et al. 2002), the feet of water starter (Hu, Chan, and Bush 2003) and the lotus leaf (Zhang et al. 2014) are typical natural superhydrophobic surfaces which give people inspirations to generate coatings with super-hydrophobicity. The superhydrophobic surface is an ideal passive anti-icing technique that its ice repellent performance has been proved is effective to mitigate ice accumulation. SHS has advantages such as low-cost icephobicity, easy to maintenance, light weight and environmental friendly. However, SHS will easily lose ice repellence ability after a short time use and is vulnerable to chemical corrosion, particle erosion and mechanical damages (Slot et al. 2015; Ishizaki, Masuda, and Sakamoto 2011; Xiu et al. 2010).
Slippery liquid-infused porous surfaces are well known for their pressure-stable omniphobicity (Wong et al. 2011), which means they are not only repellent to water (hydrophobic), but also repellent to ice (icephobic). The SLIPS are attracting great interest as a kind of anti-icing coating recently. (Stamatopoulos et al. 2017; Chen et al. 2013; Rykaczewski et al. 2013; Kreder et al. 2016) This kind of surfaces could reduce ice accumulation by allowing the condensed water droplets to slide off before they freeze. (Wong et al. 2011) The ice adhesion force on SLIPS is of 1-2 orders of magnitude lower compared to conventional materials (Vogel et al. 2013; Wong et al. 2011; Q. Liu et al. 2015), such that an easy removal of the ice formed on them can be achieved. The anti-icing performance is mainly achieved by using a slippery-oil layer in between the water and the solid substrate. Since it was found the anti-icing performance is almost independent of the underlying texture (Wong et al. 2011), the slippery lubricant plays an essential part in the anti-icing process. As a consequence, the lubricant depletion becomes a challenge for the longevity and durability for their implementation as icephobic surfaces. (Lv et al. 2014; Kreder et al. 2016; Sojoudi et al. 2016)

Traditional coating durability test mainly concerns the mechanical durability such as the adhesive durability, tangential abrasion durability, dynamic impact durability and liquid bath durability. (Milionis, Loth, and Bayer 2016) Most of them focus mainly on the damage of the solid surface morphology, which might impair the functioning mechanism such as loss of surface chemicals or hierarchical structures. However, when it comes to the application of high-speed vehicle anti-icing, the SHS and the SLIPS might encounter severe water droplet erosions, which has not been fully investigated. Especially for SLIPS, the depletion of the slippery liquid seems to be the most significant form of surface degradation. The SLIPS might
have considerable recovery ability from tape peeling or abrasion tests, but its ability to survive from liquid dynamic impact test is questionable.

Previous studies considering the water erosion durability always use relatively low impact velocities and large droplet sizes, and the speed of the spray impact is always not uniform. Liu et al. (2015) conducted a rainfall test using a pressurized water spray for their lubricant-infused electrospray silicon rubber surface. The water droplets were 300 µm–3 mm in size, with the falling height ranging from 0.5 m to 2 m. It was indicated that with an increasing water flushing time, the contact angle hysteresis has increased and the freezing time on the test surfaces has decreased. Both the hydrophobicity and the icephobicity has been significantly degraded after ten hours’ rainfall simulation. Other similar water spray durability tests were conducted by Davis et al. (2014) (impact velocity 25 m/s), Xiong et al. (2014) (impact velocity < 2 m/s) and Zhang et al. (2014) (impact velocity 7.75 m/s). However, all the test condition mentioned above were simulating rainfall’s influence on different surfaces. The droplet size was comparable to raindrops and the impact velocity was low. Water spray durability for SHS and SLIPS with finer droplet size and higher impact velocity are needed especially for scenarios when SHS or SLIPS were used as anti-icing surfaces for aircrafts or wind turbines, where the high-speed moving bodies might intercept with small droplets in clouds or atmospheric moisture.

In this study, we developed a new method to characterize the coating durability for the SHS and the SLIPS, which majorly focused on the coating erosion by water spray. We developed a high-speed spray system with controllable spray droplet speed to investigate the degrading process of the SHS and the SLIPS. Spray droplets with a mean diameter around 8 µm can be accelerated up to 95 m/s during the spray erosion test. By applying water spray with
different test durations, dynamic spray impact behaviors, impact velocities, surface properties such as the surface morphology and wettability were measured. It turns out that the SLIPS could maintain its hydrophobicity better than the SHS under a moderate spray erosion speed. The water repellent performance could be severely degraded when the microscopic structures were removed for the SHS and when the oil soaked into the porous layer was flushed away by the high-speed spray droplets. Firstly, the anti-icing performance of the SHS and the SLIPS was validated in the ISU icing research wind tunnel. Secondly, impact dynamics of an individual water droplet with Weber number around 3000 and water spray erosion behaviors on the SHS and the SLIPS were compared. Thirdly, the wettability-based coating lifetime was analyzed by measuring the dynamic contact angles on the SHS and the SLIPS with different erosion velocities. A cumulative-fatigue-damage theory was used to help predict the coating life time in in-flight aircraft anti-icing applications. Finally, the mechanism of the spray erosion for the SHS and the SLIPS was also generalized and compared. The mechanism of the spray erosion process for the SHS and the SLIPS was also compared in this study.

4.2 Experimental Methods

4.2.1 Wind Tunnel for Spray Generation

Figure 4.1. Schematic of the experimental setup for the spray generator.
In order to generate high-speed water spray for the durability test, a small wind tunnel was established. As shown in Figure 4.1, a metal ducted fan (JP 90mm 8s EDF) was used to control the wind speed. Using an electronic speed controller (ESC) (Platinum PRO V4) and an adjustable switching power supply (Volteq HY30100EX), the wind speed could be adjusted between 0 to 100 m/s. A spray system was established which includes a pneumatic spray nozzle (Ikeuchi BIMV11002), a pressurized water tank, pressure regulators, valves and tubes. The spray could be adjusted for its spray capacity by regulating the air pressure and the liquid pressure. A 3D printed nozzle holder could locate the nozzle downstream of the metal fan in the central axis of the tunnel, and the spray droplets can be fully mixed with the wind before flowing out of the outlet. The outlet had a diameter of 1 inch which was also 3D printed. The rest of the wind tunnel was made of standard PVC pipes and adapters. During the test, the test surface was mounted inside an acrylic target case, which could collect the water droplet after their collision with the test surface.

4.2.2 Spray Property Measurement

We characterized the spray by controlling the air pressure and the water pressure for the nozzle. The fine fog-like spray was steadily generated. The droplet diameter distribution was measured with the Particle Master system (LaVision). By analyzing the shadow images of the droplets illuminated by a LED lamp (Veritas miniConstellation 120 28°), the droplet diameter was found to concentrated near 6 μm and the diameter range is about 4-30 μm.
Figure 4.2. Spray property measured by PIV.

(a) Image of the water spray illuminated by the laser sheet when \( U_\infty = 42 \) m/s. (b) The contour of the velocity magnitude field superposed with streamlines when \( U_\infty = 85 \) m/s. (c) Streamwise distribution of \( U/U_\infty \) at \( Y/L = 0 \). (d) Vertical distribution of \( U/U_\infty \) at \( X/L = 0.2 \).

A macro view of the spray property was achieved using Particle Image Velocimetry (PIV). The water droplets were used as the tracer particles directly. As shown in Figure 4.2, the flow of the spray had good symmetricity. The stagnation point inside the low speed region located in the center of the spray. The spray in the current test had a shape looks like a circular cylinder after blown out from the wind tunnel’s outlet, which is different from the shape as generated directly from the nozzle. It was indicated that by fixing the air and water pressure as the same, larger wind speed will lead to sparser impact droplets due to the fixed water flow rate \( Q \). The \( LWC \) in this study would change with the wind speed \( U \) and their relation can be presented as:
\[ LWC = c \frac{PO}{U}, \]

where \( c \) is a constant related to the geometry of the wind tunnel.

### 4.2.3 Coating Preparation

The SHS coating was made by spraying Hydrobead® on well-polished aluminum plates. Aluminum is polished with sandpaper grits ranging from 220 to 2000 and further with polishing compound to achieve mirror (Beeram 2017). Both the Hydrobead® standard and the Hydrobead® enhancer were applied according to the instruction provided by the product. The distance from the spray gun to the target surface is a constant 9 inches to eliminate the difference of coating surface.

The porous layer of the SLIPS was made of a random network of Teflon nanofibrous membranes, which is commercially available from Sterlitech®. The hydrophobic membrane was laminated. Its functioning surface had an average pore size of \( \geq 200\) nm and its polypropylene backer was sticked to an aluminum substrate. The lubricating fluids used for the experiments were DuPont Krytox 103, which is one kind of clear, colorless perfluorinated oil used by Wong et al. (2011) and Liu et al. (2015). The slippery oil infused surfaces had a thickness of 60-80 µm.

Both SHS and the SLIPS were applied on 2” × 2” aluminum plates. It should be noted that the perfluorinated fluid selected for the SLIPS was Krytox® 103 since its low evaporation rate could eliminate the influence of oil depletion from evaporation. Wong at al. (2011) conducted a the evaporation measurement for the perfluorinated fluid by measuring the liquid mass loss with a high resolution balance (Mettler Toledo AT460 DeltaRange analytical balance with 0.1 mg sensitivity). They found that for the Krytox® 103, the evaporation rate is less than 0.05% per day and the changing of the surface wetting property is negligible within a 28-day
period. With a similar test condition where the temperature is 20 °C and 50% relative humidity, we assume the durability change due to evaporation of the perfluorinated fluid is unimportant.

4.2.4 Contact Angle Measurement

High-speed camera (PCO 1200hs camera) with a high 12x zoom lens system (LaVision) was used to record the static and dynamic CA. The commercial software of ImageJ was used to measure the CA information. Measurement of the static CA $\theta$ was performed by directly placing a 10 $\mu$L deionized water droplet over the test surfaces. The advancing CA $\theta_{adv}$ and receding CA $\theta_{rec}$ were measured by expanding and contracting a 50$\mu$L sessile droplet with a rate of 10 $\mu$L/s. The hysteresis is defined as the difference between $\theta_{adv}$ and $\theta_{rec}$. The water droplet was controlled by a Syringe pump (Genie Touch). The measurement was repeated at least three times for each experimental case to eliminate the random error of the measurement.

4.3 Results and Discussions

4.3.1 Comparison of Anti-Icing Performance of the SHS and the SLIPS

The anti-icing performance of three kinds of surfaces is compared in Figure 4.3 on the pressure side of the airfoil DU96-W-180. The test was completed inside an icing research wind tunnel at Iowa State University and detailed information could be referred to Liu at al. (2018). Glaze ice was generated under $LWC$ of 1.20 g/m$^3$ and temperature of -5 °C. The baseline case was applied with the coating of white enamel, which is hydrophilic. More ice was accumulated on the baseline case and there exist obvious iced rivulets, which are distributed from 0.25 to 0.5 of the chord length. In contrast, both SHS and SLIPS reduced water runback icing due to their super-hydrophobicity and hydrophobicity. In other words, water droplets are easier to roll away from the SHS and the SLIPS before freezing on the surface.
Figure 4.3. Comparison of dynamic ice accretion process over different surfaces on the DU96-W-180 airfoil under the glaze icing conditions.

(Pressure side with $U_\infty = 40\text{m/s}$, $T_\infty = -5^\circ\text{C}$, and $LWC = 1.20\text{g/m}^3$).

Even though the SHS and the SLIPS have better anti-icing performance than the baseline case, all the three surfaces have encountered ice accretion near the leading edge. After ice accretion on the leading edge, the impact ice will be formed on the ice surface, which means that a layer of ice would prevent the surface coating from damaged by the subsequent water spray or ice crystals. Note that the ice accretion on the leading edge was initialized almost at the same time within the first 30 seconds, while the water runback icing could be prevented for a much longer time on SHS and SLIPS.
4.3.2 Dynamic Impinging Process of Water Droplets at High Weber Numbers

![Image of water droplet impact dynamics on different surfaces]

Figure 4.4. Comparison of water droplet impacts dynamics onto different surfaces.

(a) Enamel coated surface, (b) SHS and (c) SLIPS. The droplet diameter is 3.1 mm and the impact velocity is 8.7 m/s (We = 3000), under room temperature.

The impact dynamics of a droplet with Weber number of 3000 are compared on the baseline surface, SHS and the SLIPS in Figure 4.4. These results were conducted in a wind tunnel which can accelerate the droplet, and the corresponding details could be found from the authors’ other works (Ma et al. 2017; Liu et al. 2018). The splashing phenomena were shared by the three surfaces in the very early stage at about 0.5 ms, while after which, the impact dynamics were very different on the three surfaces. On the hydrophilic baseline surface, water droplet would spread out as a water film with its maximum diameter remained on the surface.
On the SHS, the droplet would sufficiently expand itself into a large water film, after which the water film broke up and rebound away from the superhydrophobic surface. On the SLIPS surface, the droplet will spread into a water film firstly, and then the water film receded back to the impact location. It should be noted that after the droplet impacting onto the SHS, a smaller droplet has penetrated the micron surface structures, and it finally remained in the center of the impact location. The receding process was accompanied by the breaking up process when multiple smaller droplets were generated. From the perspective of anti-icing, all the three surfaces had more or less water remained at the impact location. This phenomenon is correlated to the results in Figure 4.3 when all the three cases had ice accreted on the leading edge. Since the SHS and SLIPS allow the water to easily roll away under the wind shear force before icing, the water runback icing can be prevented.

### 4.3.3 Initial Stage of the Spray Erosion

**Figure 4.5.** The initial stage of the water spray erosion on the SHS and the SLIPS when the $U_\infty$ is 45 m/s, LWC is 22 g/m$^3$.

(a) Spray erosion on the SHS, (b) Spray erosion on the SLIPS. Size of the FOV is about 1.5×1.5 inch.
Figure 4.5 compares the initial stage of water spray erosion for the SHS and SLIPS. At a relatively low impact velocity and high LWC in this study, SHS and SLIPS behave differently in the initial stage of the spray erosion. As shown in Figure 4.5(a), water spray generated a bright region in the center of the impact location. The reason is that before the impact of the spray, the hierarchical structure of the SHS would generate less light reflection. However, after the impingement of the spray, the hierarchical structures were saturated by the high-speed droplet and a water film is generated at the impact location. More light reflected from the aluminum substrate was allowed to go through the water film, and thus the bright spot was generated. It should be noted that the saturated water film would exist along with the water spray erosion regardless of the wind speed (from 45 m/s to 95 m/s). However, once the water spray was terminated, the water film will be rapidly evaporated by the upcoming wind and the local super-hydrophobicity could be regained.

Figure 4.5(b) presents the original stage of water spray on the SLIPS. At the snapshot of 0 sec, a bright “mirror” reflection of the LED light was achieved from the smooth oil surface with a suitable optical setup. The SLIPS was originally designed to serve when excess oil was applied (Wong et al. 2011). However, it is not necessarily to fill the SLIPS with excess oil since the oil film is vulnerable to dynamic pressures due to depletion. As shown in Figure 4.5(b), the excess oil could be easily flushed away by water spray erosion. It is the oil soaked into the porous structures that work for anti-icing applications. It is also visualized that the droplets will slide away from the stagnation point radially unless they were trapped inside the low speed region.

Results in Figure 4.5 and Figure 4.4 helps to explain why the icing on the leading edge coated with SHS and SLIPS was initialized almost at the same time with the hydrophilic
surface. Even though the SHS and the SLIPS are water repellent, the SHS will have a saturated water film generated near the stagnation point, while the SLIPS has droplets trapped inside the low speed region near the stagnation point. After the ice layer was formed on the leading edge, the functionality of the SHS and the SLIPS will be blocked.

### 4.3.4 Surface Topology of the SHS and the SLIPS

This section compares the microscopic surface topology for the SHS and the SLIPS, respectively. The surface topology of the SHS is measured by Atomic Force Microscope (AFM) while the surface topology of the SLIPS is measured by Confocal Laser Scanning Microscopy (CLSM). Although AFM measurement is supposed to have higher resolutions, we use CLSM to measure the SLIPS since the oil layer over the SLIPS is hard to be directly measured using AFM.

![AFM scanned surface topology images of SHS with the spray impact velocity of 65m/s.](image)

(a) non-damaged; (b) after 10 min; (c) after 30 min; (d) after 50 min.
As shown in Figure 4.6, the hierarchical structures over the SHS are flattened after spray erosion. Like most lotus-leaf-inspired SHS (Cheng et al. 2006), two mound-like structures are captured in the non-damaged SHS surface in Figure 4.6(a). These raised mound-like structures are of the micro-scale and they are gradually washed out as the spray erosion duration increases. It is clearly observed that the averaged roughness (Ra) decreases from 1.22 μm to 0.43 μm. Although the damage of the nano-scale structures is not evident, it could be inferred from the AFM measurement that the loss of the mound-like structures caused the Ra decrease. The change of the surface topology is directly related to the hydrophobicity degradation (Cheng et al. 2006), and in this study an increased hysteresis value of more than 40° is induced.

Figure 4.7. CLSM scanned surface topology images of SLIPS with the spray impact velocity of 75m/s.

(a) Without oil; (b) with oil non damaged; (c) with oil after 30 min; (d) with oil after 90 min.
As shown in Figure 4.7, the surface topology of the SLIPS is measured by the CLSM technique. Comparing Figure 4.7 (a) and (b), the original substrate with random network fabric has a larger roughness, and the roughness value decreased after the application of the oil. Results from Figure 4.7 (a) and (b) shown that the oil layer could infuse the valleys of the substrate. Note that the accuracy of the CLSM measurement for a liquid layer is not clear. The bare tops not submerged by the oil as shown in Figure 4.7 (b) could still maintain an oil layer considering the changed texture in comparison with that shown in Figure 4.7 (a). After the water spray is applied as shown in Figure 4.7 (c) and (d), the recovered roughness values indicate that the excess oil has been removed. The wettability of the surface could be significantly influenced by the excess oil depletion as would be shown in the following sections. The similarity between Figure 4.7 (c) and (d) shows that the lubricant oil remained inside the nano-scale porous structures appears to be more resistant to the spray erosion. As mentioned in later sections, the relatively steady wettability of the SLIPS after spray erosion turns out to be majorly maintained by the oil inside the nano-scale structures of the porous substrate.

4.3.5 Wettability Based Lifetime Subject to Spray Impingement

After the initial stage of water spray erosion, no visible surface degradation could be detected until the macro structural defects are generated. In order to characterize the surface performance quantitatively, the surface wettability was measured at different spray erosion durations. We assume that only physical damages are caused to the surface and the damages are accumulated by repeated impingement of individual droplet of the same radius from the water spray. Since the LWC and the wind speed are correlated in this study, it is fairer to use the count of droplet impingement as the dimensionless time. Assume the droplet are perfectly sphere and they share the same radius $R$, the count of impingement is given by:
\[ N = \frac{n\pi R^2}{S} \]  

(4.2)

\( N \) could be understood as the number of duty cycles of the repeated damage of droplet impingement. The total number of droplets \( n \) can be calculated by using the ratio between the mass of the water released from the wind tunnel outlet and the mass of the individual droplet:

\[ n = \frac{LWC \cdot t \cdot U \cdot S}{\frac{4}{3} \rho \pi R^3}. \]  

(4.3)

Substituting \( n \) in Eq. 2, the count of droplet impingement can be expressed as:

\[ N = \frac{3LWC \cdot t \cdot U}{4 \rho R} \]  

(4.4)

Given Eq. 1, \( N \) is linearly related to \( t \) for all the test case in this study since the flow rate of the spray system was maintained the same by fixing the nozzle’s water pressure and air pressure as constants. To provide a reference point to calculate the \( N \), we measured the \( LWC \) when the \( U_\infty \) is 65 m/s and the corresponding \( LWC \) is 15 g/m\(^3\).

To achieve a parameter which could quantitatively represent the coating lifetime, both the static and the dynamic CA were measured. For the static CA, the SHS has a static CA decreasing with the spray erosion duration (from above 155° to below 135° when \( U_\infty \) is 95 m/s), while the SLIPS will retain its static CA as 112° ± 5° after a long duration of spray erosion. Static CA is thus not considered to serve as a general indicator of the coating lifetime in this study. For the dynamic CA, it was observed that both the SHS and the SLIPS would have their advancing CA kept steady. For all cases tested on SHS, the advancing CA is 165° ± 5°, and on the SLIPS the advancing CA is 115° ± 5°. As a result, the hysteresis variation is majorly determined by the receding CA according to its definition.
Figure 4.8. Hysteresis variation as a function of count of droplet impingement on the SHS and SLIPS.

Figure 4.8 presents the hysteresis variation for the SHS and the SLIPS. Hysteresis will increase with the spray erosion time and finally reach a plateau, which means the water repellency of the SHS and the SLIPS would gradually degrade, and a steady state could be maintained after the degradation. Note that the SHS has its final hysteresis increased with the enlarging spray speed, while the SLIPS seems to have all the cases ended up with the same hysteresis. In addition, the change scale for the SHS (ranging from 75° to 115°) is much larger than that of the SLIPS (less than 25°). Under the same wind speed, the SLIPS appeared to be more durable than the SHS since more droplet impact duty cycles are needed for SLIPS to reach the steady hysteresis value.
Figure 4.9. The damage-cycle relationship for the SHS and the SLIPS.

We define $N_0$ as the wettability-based coating lifetime, and it is the count of droplet impingement $N$ when the steady hysteresis is reached. Use the cumulative-fatigue-damage theory (Kaechele 1963), we define a damage level $DL$ to represent how close the current hysteresis state is to its final steady state.

$$DL = \frac{\theta_{h,\text{current}} - \theta_{h,\text{initial}}}{\theta_{h,\text{final}} - \theta_{h,\text{initial}}}$$ (4.5)

As shown in Equation. 4.5, the initial state has a $DL = 0$, which means no damage was generated to the surface wettability. While the final state has a $DL = 1$, which means the damage has been completed. Results in Figure 4.8 for both the SHS and the SLIPS could be normalized as a damage-cycle relationship as shown in Figure 4.9. By selecting suitable $N_0$, all the hysteresis curves will collapse into one. Even though the uncertainty is rather large due to the large standard deviation value from the CA measurement, the trend lines fitted for all the cases either from the SHS or the SLIPS are very close to each other, which means the damage-cycle relationship is independent of the surface we applied. Current results have
shown no clue whether the damage-cycle relation is dependent on the spray impact velocity or not, since the deviations caused by the impact velocity could be a result from the measurement uncertainty or a bad selection of $N_0$.

![Figure 4.10](image)

**Figure 4.10. Comparison of a wettability-based lifetime for the SHS and the SLIPS regarding spray speed.**

Figure 4.10 compares the wettability-based lifetime for the SHS and the SLIPS regarding the spray speed. The SLIPS is almost 3 times more durable than the SHS when the spray speed is less than 85 m/s according to the results from this study. Second order polynomials are used to fit the trend lines and there is no clue whether extrapolation of the relation works under spray speeds beyond the current experimental setup. However, this relation between $N_0$ and $U_∞$ can be helpful to the prediction of the coating lifetime for inflight-aircrafts using same coatings from this study. For example, given a specific wind speed $U_∞$, the corresponding wettability-related coating lifetime $N_0$ can be calculated. Plug back into $N_0$ and $U_∞$ Eq. 4, a lifetime in $t$ can be estimated given the LWC if the geometry of the droplets is similar.
4.3.6 Final Surface Damage Styles

![Figures showing surface damages styles](image)

*Figure 4.11. Typical surface damage styles for the SLIPS under water spray erosion. (wind speed is 75 m/s)*

In this study, there is visible structural damage to the SLIPS in the final stage of the water spray erosion. As shown in Figure 4.11, two sorts of surface damages styles are compared when the spray speed is 75 m/s. Images in the upper row and lower row present damage results for surfaces without and with slippery oil, respectively. Visible structural damage appears much earlier when no oil is applied, and the porous layer will be torn up by the water spray within 10 minutes. Three regions near the damaged spots are selected to present the surface morphologies with a 40x magnification. Scopes A, B and C are corresponding to the regions of the undamaged surface, the edge and the center of the defect region. The original surface shown in Scope A has a relatively smooth texture, which represents the laminated PTFE membrane surface. As shown in Scope C, the porous layers have been smashed apart from the substrate layer, and the fragments of the porous layer after being blown to the edge of the defect spot are presented in Scope B. During the experiment, water could penetrate from the defect region and enter between the aluminum surface and the PTFE membrane.
Different from the results in the upper row, the PTFE membrane appears to be more durable after the slippery oil is applied. The oiled surface would be damaged after about 60 minutes of spray erosion. Moreover, the damage style is also different. As shown in Scope D, water has accumulated in between the porous layer and the substrate fabric. The evidence could be observed from the enlarged view of Scope E, where both air and water were trapped beneath the porous layer. Scope F presents the defect spot after 180 minutes’ spray erosion. It is shown that with a longer duration of spray erosion, more defect spots will appear. What’s more, surface contaminations were observed as black dust. These contaminations would accumulate on the SLIPS and the local wettability would be changed since the dust appeared to be hydrophilic.

4.3.7 Mechanism of the Spray Erosion for the SHS and the SLIPS

![Figure 4.12. Mechanism of surface degradation by spray erosion for the SHS and the SLIPS.](image)

According to the previous discussion, the surface degradation mechanism of spray erosion is generalized in Figure 4.12. For the Hydrobead® coated SHS, it is the micro- and nanoscopic architecture on the surface that can maintain the low hysteresis of the surface (Cheng et al. 2006). However, under water spray erosion, this hierarchical architecture is
vulnerable to the repeated water droplets impingement. The damage of the microscopic mound-like structure of the SHS was visualized using AFM. Other indicators of the damage are represented by parameters of the surface wettability. An increased CA hysteresis was observed on the SHS and then the value of the hysteresis will reach a plateau, which was considered as a functional lifetime for the SHS. The longer duration of water erosion would finally remove the coating from the substrate materials.

For the PTFE based SLIPS coating, the slippery oil plays an essential part to maintain its functionality. The extra oil applied to the PTFE laminates membrane could be rapidly removed either by the flow or the water spray. Thus, the water repellency is achieved by the nanoscopic porous structure with oil soaked inside. We assumed the oil depletion is the cause of the surface degradation according to the fact that the SLIPS could recover to its original state with oil refilled. In this study, even though the oil inside the porous layer is not effectively visualized, the degradation of the SLIPS is measured according to the wettability information. Similar to the SHS surface, the SLIPS would also firstly have its CA hysteresis increases with the spray erosion time, and then reaches a plateau. When the SLIPS is left to the water erosion with a long time without refilling oil, the porous layer would either detach or be entirely removed from the substrate layer, and this kind of damage is unrecoverable.

4.4 Conclusion

In summary, the durability of the Hydrobead® coated SHS and the PTFE-membrane-based SLIPS was tested and compared under water spray erosion. A small wind tunnel was established so that the spray speed could be controlled by a metal ducted fan. During the test, the droplet impact speed was varied from 45 to 95 m/s. The anti-icing performance of the SHS and the SLIPS was validated in comparison with the hydrophilic surface. The results indicate that the SHS and SLIPS coatings could effectively prevent the water runback icing under glaze
ice condition. Droplet impact dynamics were also presented, which indicates that the low hysteresis of the SHS and SLIPS could allow more water to be blown away by the ambient wind after the impingement. By visualizing the early stage of water spray erosion on the SHS and the SLIPS, it was observed that both the SHS and the SLIPS are not repellent to spray impingement. It is because a saturated water film would be generated for the SHS and remained water droplet would be trapped in the low speed region near the stagnation point for the SLIPS. These findings could help to explain why the impact icing is inevitable, but the water runback icing could be effectively avoided.

Furthermore, the wettability-based coating lifetime is analyzed by measuring the dynamic contact angles on the SHS and the SLIPS under water spray erosions with different velocities. It was found that the advancing CA would remain almost the same during spray erosion. However, the hysteresis of the two kinds of coatings will gradually increase until a plateau was reached. According to this phenomenon, a dimensionless damage level was defined for the hysteresis based on the cumulative-fatigue-damage theory. By fitting the trendline for the relation between the wettability-based coating lifetime and the spray erosion velocity, helpful predictions for the coating lifetime applied for in-flight aircraft anti-icing was achieved. It turns out that the SLIPS could maintain its hydrophobicity better than the SHS under a moderate spray erosion speed. The mechanism of the spray erosion process for the SHS and the SLIPS was also compared in this study. Besides the traditional mechanical durability test, we suggest taking spray erosion test into consideration when the SHS and SLIP surfaces are applied into scenarios where high-speed water droplet erosion is present like application on vehicles, wind turbines and aircrafts.
References

Beeram PSR. 2017. “Characterization of Ice Adhesion Strength over Different Surfaces Pertinent to Aircraft Anti-/de-Icing.” Iowa State University, Graduate Theses and Dissertations, January.


CHAPTER 5
AN EXPERIMENTAL INVESTIGATION ON WIND-DRIVEN DROPLET MOVING ON SURFACES WITH DIFFERENT WETTABILITIES

Liqun Ma, Yang Liu, Hui Hu
Department of Aerospace Engineering, Iowa State University, Ames, Iowa, 50011

Abstract

Wind-driven droplet motion over a flat plate is a problem of fundamental importance for the understanding of the aircraft/wind turbine water runback icing processes. In this paper, the critical wind speed which can start the incipient motion of a sessile droplet was experimentally measured and theoretically predicted. Particle Image Velocimetry (PIV) technique was applied for measurement of the velocity field around the sessile water droplet. With the detailed information about the flow field around the droplet and the droplet profile, the aerodynamic force and the adhesion force could be calculated. The force balance for the droplet incipient motion was validated in order to use the theoretical model to predict the critical wind speed. It was found the transition process on the flat plate could influence the determination of the critical wind speed. The critical wind speed has a power relation with the droplet volume, and the power indices range from -1.9 to -1.3 for current surfaces in this study. It was also noticed that the distance to the leading edge could significantly influence the critical wind speed especially for smaller droplets.

5.1 Introduction

Icing is widely recognized as one of the most serious weather hazards to inflight aircrafts. (Gent at al. 2000) Airborne water droplets from clouds and fog would majorly form two distinct ice types as the rime ice and the glaze ice under different temperature and liquid
water content ($LWC$) levels. Low-temperature ($T<-10^\circ C$) and low-$LWC$ would usually generate rime ice since water droplet would freeze upon impingement and air could be trapped inside during ice accretion. On the other hand, high-temperature ($-10^\circ C<T<0^\circ C$) and high-$LWC$ usually generate glaze ice when part of the water droplet would remain as liquid phase, and runback and freeze outside of the impact region. (Liu et al. 2017) Anti-icing systems for aircraft usually use surface coatings and heaters to avoid ice accretion in the leading edge, so that water droplets remained on the surface could be blown away before frozen. (Goto 2005)

It is of fundamental importance to understand the shedding of sessile droplets by airflow, since the corresponding knowledge would help to design more efficient anti-icing systems for inflight aircrafts.

With the rapid development of surface engineering, a series of special surface coatings succeed in ice mitigation using airflow to remove the remained water. These sophisticated surfaces include but not limited to super-hydrophobic surfaces (SHS), PDMS gel surfaces. SHS has a water droplet contact angle (CA) larger than $150^\circ$ and a sliding angle (SA) less than $10^\circ$ (Li at al. 2007; Bhushan and Jung 2011). SHS always has a hierarchical structure which is similar to the lotus leaf (Cheng et al. 2006), and water droplets on SHS appear as water beads which can easily roll off the surface by wind or gravity before frozen (Wang et al. 2013). More recently, it is found that soft PDMS gel surfaces have durable anti-icing performance for inflight aircraft. (Beemer at al. 2016; Liu et al. 2018) Water droplets would not only rebound away from the surface after impingement (Ma et al. 2018; Liu et al. 2018), but also be able to roll away before frozen due to the hydrophobicity of PDMS. Considering the differences in wettabilities and mechanisms of water repellency, it is necessary to have a systematic
understanding of how efficient the surfaces are when the aerodynamic force is applied to remove the adhered water droplets.

A quantitative water shedding model involving wind speed, droplet volume and surface wettability would help engineers select promising anti-icing surfaces for high-speed trains, inflight aircrafts and wind turbines, where aerodynamic force plays a major part to remove the water droplets. Previous theoretical models are mostly based on the force balance where the external flow is considered as shear flow (Dussan V. 1987; Ding, Gilani, and Spelt 2010) or uniform inviscid flow (Durbin 1988). Actually, the aerodynamic force produced by the external flow is a complicated part due to the existence of the boundary layer. Roisman at al. (2015) checked the existing models and found they failed to predict the critical wind speed which initiates the droplet dislodging even in order of magnitude. Recent models (Milne and Amirfazli 2009; Moghtadernejad et al. 2015; Roisman et al. 2015) predicting the critical wind speed usually consider the lateral force balance between the droplet adhesion force $F_{adh} = w\gamma(\cos\theta_{up} - \cos\theta_{down})$ and the aerodynamic drag $F_{drag} = \frac{1}{2}\rho U^2 AC_D$. For the adhesion force equation experimentally validated by Pilat at al. (2012), $w$ is the droplet width, $\gamma$ is the surface tension, and $\theta_{up}, \theta_{down}$ are the droplet contact angles dewetting and wetting the surface. For the aerodynamic drag force equation, $\rho$ is the air density, $U$ is the wind speed in the vicinity of the droplet, $A$ is the droplet projected area to the wind, and $C_D$ the drag coefficient. The critical wind speed is achieved by solving $U$ when $F_{adh}$ and $F_{drag}$ are balanced.

Although several experimental investigations have explored the critical wind speed which can initiate the droplet incipient motion, the detailed flow field in the vicinity of the droplet is not presented. In most of the previous tests, only the boundary layer thickness is provided for the flow field around the droplet. The thickness of the laminar boundary layer $\delta$
is usually estimated from the Blasius solution, \( \delta \approx 5 \sqrt{\nu x / U_\infty} \), where \( \nu \) is the kinetic viscosity of the air, \( x \) is the distance downstream of the leading edge of the flat plate, and \( U_\infty \) is the velocity of the freestream wind. Milne and Amirfazli (2009) changes the droplet volumes so that the droplet height ranges from approximately 0.9 to 2.5 times the theoretically estimated boundary layer thickness (\( x \) is 10 cm and maximum \( U_\infty \) is 30 m/s). By changing the wind speed from 5 m/s to 90 m/s, Moghtadernejad at al. (2015) estimated the ratio of droplet height to boundary layer thickness to range from 1.488 to 11.875 when the surface wettability was changed. The boundary layer thickness calculated by Roisman at al. (2015) ranges from 1.4 mm to 2.5 mm, which is of the same order of magnitude as the height of the droplet in their experiment. However, the flow field information around a droplet is far from sufficient solely provided with the boundary layer thickness. With a changing surface wettability, the shape of the droplet could change from a hump to a bead (Öner and McCarthy 2000). The existence of the droplet could significantly alter the local flow field due to flow separation, and a low speed region will be generated behind the droplet (Durbin 1988). For this form drag predominated situation, the interaction between droplet deformation and transient flow field would also make contributions to the incipient motion of the droplet. Detailed flow information around the droplet could help to develop more accurate models which can predict the droplet motions over surfaces with different wettabilities under wind shear force.

In this paper, wind-driven droplet shedding is measured by PIV technique on surfaces with various wettabilities, such as PC, PDMS and SHS. Water droplets with volumes changing from 10 to 100 \( \mu \)L were tested under different wind speed. Firstly, the velocity field around the droplet is presented during the incipient motion phase. Statistics of the velocity fields are presented and compared for different surfaces. Secondly, the critical wind speed is presented
as a function of the droplet volume on different surfaces. Finally, a theoretical model with more details in the ambient flow field was generated and validated using the current and previous experimental results.

5.2 Experimental Methods

5.2.1 PIV Measurement

![Figure 5.1. Schematic experimental setup for PIV measurement](image)

In the current study, a high-resolution digital Particle Image Velocimetry (PIV) system was used to quantify the flow characteristics of the boundary layer flow around the droplet. The schematic of the PIV measurement setup is shown in Figure 5.1. The upcoming flow was provided by an open circuit low-speed wind tunnel, whose outlet had a dimension of $W \times H = 8'' \times 5''$. The coated substrate was an acrylic plate with a dimension of $W \times L \times T = 5'' \times 10'' \times 0.5''$. The acrylic plate was fixed on a lab jack so that the upper surface could be adjusted to the same level with the bottom of the wind tunnel outlet. The leading edge was $45^\circ$ chamfered and a 10 mm gap was maintained in order to reduce the boundary layer's effect from the wind tunnel. During the test, the wind speed could be controlled from 0 to 30 m/s by adjusting the motor speed. The airflow was seeded with $\sim 1\mu$m oil droplets generated by a smoke generator. The
illumination was provided by a double-pulsed Nd: YAG laser (New wave Gemini 200), which emits two pulses of 200 mJ at the wavelength of 532 nm. A Fastcam Mini WX100 camera (Photron) was synchronized with the laser by a pulse generator (Model 565, BNC). The measurement window is 20 × 10 mm and the corresponding image size is 2048 × 1024 pixels. The water droplet was seeded using the carboxylate-modified microspheres (FluoSpheres®), which is 1.0 μm in diameter and has a nile red fluorescent emission light at the wavelength of 575 nm. The droplet was released using a Pipette for each run and the droplet volume in this study was varied from 5 to 100 μL on various surfaces. The droplet was located at the same streamwise location and the measurement window is about 15 mm downstream of the leading edge of the substrate. For PIV image processing, flow velocity vectors were achieved using the cross-correlation technique between the PIV raw-image pairs. The interrogation window has a size of 32×32 pixels. An effective overlap of 50% of interrogation windows was employed in the PIV processing. The sampling frequency is 15 Hz and the Δt between two consecutive laser pulses is 6 μs. In this manner, the typical particle displacement is within 10 pixels when the free stream velocity is 15 m/s.

5.2.2 Surface Preparation

The Polycarbonate (PC) surface was a strong, tough and sometimes transparent material used in engineering. The PC surface was used once after the protection sticker is removed.

The SHS coating was made by spraying the commercially available Hydrobead® on the reference plates. Both the Hydrobead® standard and the Hydrobead® enhancer were applied according to the instruction provided by the product. The distance from the spray gun to the target surface is a constant 9 inches to eliminate the difference of coating surface.
The PDMS is a hydrophobic material which is commercially available, inexpensive and environmentally benign. (Beemer et al. 2016) The PDMS gels were fabricated via hydrosilylation of vinyl-terminated PDMS, v-PDMS with hydride-terminated PDMS, h-PDMS. The shear modulus was tuned by adding different amounts and different molecular weights of non-reactive trimethyl-terminated PDMS (t-PDMS), to the hydrosilylation mixture. (Beemer et al. 2016) The shear modulus of the PDMS gels monotonically decreased with the increasing concentration of t-PDMS in the hydrosilylation mixture. More detailed information for the fabrication of the soft surfaces in this paper can be referred to Beemer et al. (2016). In this study, the thickness of the PDMS surfaces was 200 μm. The 20% t-PDMS soft surfaces were settled on 10 in × 5 in flat acrylic plates, which were able to be mounted at the top of the substrate for the wind-driven droplet movement tests.

The common static contact angles for the PC, PDMS and SHS from literature are 82°, 107.2° and 156°, respectively. (Enterprises 2009)

5.2.3 Image Post Processing

In this study, the droplet shape could be subtracted from the raw images of PIV measurement. For each pulse of the laser sheet, the fluorescence particles inside the droplet could be illuminated simultaneously. Since the concentration of the fluorescence solution is relatively high, the whole droplet appears as a bright region, which can be easily separated from the raw image using a custom MATLAB code. The raw image was firstly binarized and pixels representing smoke particles were removed due to their low connectivity level. The substrate would appear as a straight bright line in the raw image and the boundary of the substrate was detected by manually inputting its position. Holes in the droplet region was then filled so that the droplet could be recognized as a solid region and its boundary line could be detected. The advancing and receding points were defined as the intersection points between
the substrate boundary line and the droplet boundary line. The advancing and receding contact angles are calculated by finding the tangent line across the advancing and the receding points for the second order fitted droplet boundary curves.

5.3 Force Balance Analysis

Figure 5.2. Side view of a wind-driven droplet

Wind-driven droplet over the horizontal flat plate majorly subject to two sources of force. As shown in Figure 5.2, one of them is the lateral adhesion force $F_{\text{adh}}$ caused by the liquid surface tension on the liquid-solid-air interface. The other is the aerodynamic force $F_{\text{aero}}$ exerted by the upcoming wind which is parallel to the plate surface. If the two forces are not balanced, as shown in Figure 5.2, the inertia would come into play. The wind-driven droplet will always have

$$F_{\text{adh}} + F_{\text{aero}} + F_a = 0. \quad (5.1)$$

5.3.1 Adhesion Force

According to Antonini at al. (2009), the adhesion force of the drop is controlled by surface tension, contact angles, and the shape and length of the contact line. Since the droplet has a 3D surface and the contact angle during sliding is actually varying along the circle of the
three-phase contact line. By integrating the surface tension, the adhesion force of the droplet is given by:

\[ F_{adh} = -\gamma \int_0^L \cos \theta(l) \cos \psi(l) dl. \]  

(5.2)

dl running from 0 at the downstream contact point of the contact line counterclockwise around the length of the contact line \( L \). The function \( \psi(l) \) describes the distribution of the normal of the contact line, whereas \( \theta(l) \) describes the distribution of the contact angle along the same. (Milne and Amirfazli 2009)

Since this study only has a side view of the droplet, only the advancing and receding contact angles could be achieved. Following the reference of Dussan (1987), Pilat at al. (2012) and Roisman at al. (2015), a simplified adhesion force equation is used as:

\[ F_{adh} = kw \gamma (\cos \theta_{rec} - \cos \theta_{adv}), \]  

(5.3)

where \( w \) is the length of the droplet base as viewed, \( \gamma \) is the surface tension and \( \theta_{rec}, \theta_{adv} \) are the dewetting and wetting contact angles when the droplet moves over the solid surface, respectively. Note that a constant \( k \) was used similarly to the study by Milne and Amirfazli (2009). We used this \( k \) to eliminate the bias from the side viewed 2D contact angles regarding the actual 3D contact angles distributed along the droplet contact line.

5.3.2 Aerodynamic Force

The aerodynamic force estimation over the sessile droplet need take both the boundary layer effect and the droplet profile into consideration. Firstly, the large velocity gradient inside the boundary layer plays a significant role when calculating the aerodynamic force considering the droplet height is comparable to the boundary layer thickness. Secondly, the droplet profiles change with different droplet volumes and surface wettabilities, which means different aerodynamic forces could be generated even under the same velocity profiles. Finally, it is
essential to have a reasonable estimation on both the droplet profiles and the velocity profiles, so that the aerodynamic force could be predicted. In this study, due to the application of the PIV technique, variations of the velocity profile around the changing droplet profiles could be achieved with reasonable resolution. As a consequence, a theoretical aerodynamic force could be estimated and validated with the experimental measurement.

5.3.2.1 Control Volume Based Estimation

![Diagram of control volume for wind-driven droplet]

As shown in Figure 5.3, a control volume is generated around the wind-driven droplet. Interface 1 and 2 denote the wind inlet and outlet for the control volume, respectively. Interface 2 represents the far field above the solid surface when the velocity has recovered to the freestream velocity. Interface 4 is the solid surface not covered by the droplet. Interface 5 represents the droplet surface. Note that the 2D control volume vertically crosses the center of the droplet and it is parallel to the wind speed. Consider the momentum equation over the control volume:

\[
\frac{\partial}{\partial t} \iiint_V \rho \mathbf{V} \, dV + \iiint_S (\rho \mathbf{V} \cdot dS) \mathbf{V} = -\iiint_{l-S} \rho dS \cdot \mathbf{R}'.
\]  

(5.4)

We regard the flow field as a steady one when the critical wind speed is reached so that the first term on the left side of Equation 5.4 could be cancelled. We neglected the pressure
change over the control volume considering the low wind speed. As a result, the horizontal component of the force $R'$ exerted over the control volume is:

$$D = -\iiint_\Omega (\rho \mathbf{V} \cdot d\mathbf{S}) u = \int_1^2 \rho u_1^2 dz - \int_3^4 \rho u_3^2 dz.$$  \hspace{1cm} (5.5)

Note that neither $u_1$ nor $u_3$ is a constant, and thus the expression in Equation 5.5 could not be simplified based on the continuity equation. There are at least two problems to use this equation to theoretically estimate the drag force $D$. Firstly, when theoretically predicting the drag force over the control volume, it is hard to achieve the velocity profile of $u_3$. Secondly, even though the drag force is successfully calculated, the drag force would consist of both the droplet drag and the surface friction, which need further information to decouple them. As a result, when theoretically estimating the aerodynamic force over the droplet, the control volume analysis could be limited in efficiency.

### 5.3.2.2 Pressure Based Estimation

In this study, the aerodynamic force is estimated by

$$F_{\text{aero}} = \int_0^H \frac{1}{2} \rho u^2 y dz.$$  \hspace{1cm} (5.6)

where $\rho$ is the water density, $z$ is the vertical locations normal to the surface, $H$ is the droplet height, $u(z)$ is the velocity profile in front of the droplet and $y(z)$ is the droplet profile (as shown in Figure 5.2). Note that we estimate the local pressure difference over the droplet is $p(z) \approx \rho u(z)^2/2$. We use the projected area of the droplet to conduct the integration. Since we don’t have the projected area of the droplet from the side view information, we assume the projected droplet profile is the same with the initial droplet profile. Since the droplet profile is axial symmetric at the initial condition with 0 wind speed, we used the initial droplet profile of the side view to calculate the experimental $F_{\text{aero}}$. When integrating the $F_{\text{aero}}$, the $\delta F_{\text{aero}}$ is equal to $p(z)y(z)\delta z$. Note that a similar method has been used by Milne and Amirfazli (2009) and
Roisman et al. (2015). However, both the velocity profile and the droplet profile have not been thoroughly considered. The velocity profile $u(z)$ and the droplet profile $y(z)$ needed in this step are calculated based on the following two subsections.

### 5.3.2.3 Velocity Profile Estimation

The velocity in front of the droplet is estimated according to the boundary layer theory. For a laminar boundary layer, the boundary layer thickness and the velocity profile are (according to Blasius solution):

$$ \frac{\delta}{x} = \frac{5}{\sqrt{Re_x}}, \quad (5.7) $$

$$ \frac{u}{U} = 2 \left( \frac{z}{\delta} \right) \left( \frac{z}{\delta} \right)^2. \quad (5.8) $$

For a turbulent boundary layer, the boundary layer thickness and the velocity profile are (according to Prandtl approximation):

$$ \frac{\delta}{x} = \frac{0.16}{(Re_x)^{\frac{1}{7}}}, \quad (5.9) $$

$$ \frac{u}{U} = \left( \frac{z}{\delta} \right)^{\frac{1}{7}}. \quad (5.10) $$

Here, $\delta$ is the boundary layer thickness, $x$ is the streamwise distance to the leading edge, $U$ is the freestream velocity, $u$ is the local velocity inside the boundary layer and the Reynolds number is $Re_x = \frac{\rho U x}{\mu}$.

### 5.3.2.4 Droplet Profile Estimation

The droplet volumes tested in this study could lead to a droplet diameter larger than the droplet capillary length $\lambda_c = \frac{\sqrt{\gamma}}{\sqrt{\rho g}}$, which is 0.273 cm ($vol \approx 10 \mu L$) for the water-air interface at standard temperature and pressure (Shi et al. 2018). The Young-Laplace fit to estimate the droplet profiles instead of the hemispherical model. It should be noted that the droplet profile
is estimated for the static axisymmetric sessile drops with gravity considered. We assume the
droplet has the same projected profile subject to the wind during the process of incipient
motion. The droplet profile could be numerically achieved by solving the system of ordinary
differential equations as listed below from Río and Neumann (1997).

\[ \frac{dx}{ds} = \cos \theta , \]  
\[ \frac{dz}{ds} = \sin \theta , \]  
\[ \frac{d\theta}{ds} = 2b + cz - \frac{\sin \theta}{x} , \]  
\[ \frac{dV}{ds} = \pi x^2 \sin \theta , \]  
\[ \frac{dA}{ds} = 2\pi x , \]

\( x(0) = z(0) = \theta(0) = V(0) = A(0) = 0 \),

where \( s \) is the arc length, \( \theta \) is the tangential angle, \( V \) is the droplet volume and \( A \) is the droplet
surface area, \( b \) is the curvature at the origin of coordinates and \( c = (\Delta \rho)g/\gamma \) is the capillary
constant of the system. It has been verified by a lot of researchers that the Young-Laplace fit
could give a perfect estimation for sessile droplet profiles under various contact angles and
droplet volumes. When calculating the critical velocity which dislodges the droplet, \( F_{aero} \) and
\( F_{adh} \) would be balanced and the critical velocity \( u_{crit} \) could be solved numerically.
Figure 5.4. *Comparison of the estimated projected droplet profile (red curve) and the raw image during droplet motion on the PDMS surface.*

Figure 5.4 presents the estimation of the projected droplet surface profile over the side view image of the initial droplet. For different droplet volumes, the estimated red curves approximately fit with the droplet in the raw image. In addition, the droplet profile is obviously not truncated circles, which indicates the advantages of using the Young-Laplace fit instead of a truncated sphere fit for the droplet profile prediction.

### 5.3.3 Inertia Force

During the process of droplet moving, if the adhesion force and the aerodynamic force are not balanced, the droplet should have an acceleration $a$ such that the inertia force $F_a = F_{\text{aero}} - F_{\text{adh}}$. Apparently, we can also find the inertia force dynamical as $F_a = ma$. However, note that the droplet actually could not be regarded as a rigid body when considering its movement physically. A discrepancy could exist for the $F_a$ values achieved from these two different methods.
5.4 Results and Discussions

5.4.1 Typical Initial Motion of Droplet

Figure 5.5. PIV measurement results for the wind-driven droplet movement on the PDMS surface.

(a) Raw image of PIV measurement; (b) Contour of velocity magnitude field overlapped with velocity vector field.
In order to capture the incipient motion of the wind-driven droplet, the wind speed was increased from zero to the velocity just above the critical wind speed. As shown in Figure 5.5, the incipient motion of the droplet on the PDMS surface was taken as an example to show the flow field around the droplet. Figure 5.5 (a) presents the raw images for the PIV measurement. It can be observed that the substrate and the droplet appear as bright regions, which can be easily separated from the PIV particles during PIV post-processing. Glare from the substrate and the droplet could be observed but the influence is not significant, so that the calculation of the velocity field could be trusted. Figure 5.5 (b) shows the flow field around the droplet. It is obvious that the boundary layer thickness is smaller than the droplet height but they are of the same order. Flow passing the droplet would separate from the upper bound of the droplet and a separation vortex could be generated. The interesting finding is that the droplet motion is highly influenced by the flow in the boundary layer, which incorporates complex flows like separations and vortex shedding.

\[ U_{\text{crit}} = 4.75 \text{m/s} \]

\[ \text{Position} [\text{mm}] \]

\[ \text{Wind speed} [\text{m/s}] \]

\[ \theta_{\text{adv}} \]

\[ \theta_{\text{rec}} \]

\[ \theta_{\text{adv, filled}} \]

\[ \theta_{\text{rec, filled}} \]

**Figure 5.6.** Droplet advancing and receding point positions and freestream wind speed variation on the PDMS surface (droplet volume is 40μL).

(a) Variation of advancing and receding contact points and variation of the wind speed in the freestream; (b) variation of the advancing and receding contact angles.
Figure 5.6 presents the quantitative results for the reference case where the droplet is moving on the PDMS surface. As shown in Figure 5.6(a), the freestream wind speed was increased from 0.0 to 8.4 m/s within about 4 seconds and then the wind speed was maintained the same. The droplet position was firstly fixed and then the droplet gradually moved downstream. Following the definition of the incipient motion mentioned by Milne and Amirfazli (2009), the critical wind speed could be determined from this figure by defining a displacement threshold for both the advancing and receding points, and the corresponding wind speed at the same instance was selected as the critical wind speed. As shown in Figure 5.6(a), the critical velocity is 4.75 m/s with a 10-pix threshold. It should be noticed that the averaged droplet movement speed can also be achieved from this figure after the droplet starts its motion.

Figure 5.6(b) shows the variation of the CAs for both the advancing and the receding points. The initial CA is around 100° which indicates the hydrophobicity of the PDMS surface. After the wind is on, the droplet started to deform with an increasing $\theta_{\text{adv}}$ and a decreasing $\theta_{\text{rec}}$. Until the $\theta_{\text{adv}}$ had reached above 100° and $\theta_{\text{rec}}$ had decreased to below 80° (at the instance of 2.7s) the droplet started to move on the surface. During the deformation, the capillary force of the droplet is increased and the droplet starts to move when the wind induced drag reached the balance with the capillary force.

### 5.4.2 Drag Estimation

As the freestream velocity is increasing from the still state, the boundary layer condition is expected to change along with the course of the laminar state, transition state and turbulent state. In this study, since the turbulence intensity of the open circuit wind tunnel is not well controlled, the critical Reynolds number which indicates the transition from the laminar state to the turbulent state could not be determined. However, the transition from the laminar state to the turbulent state could be captured by analyzing the velocity profiles in front...
of the droplet. As shown in Figure 5.7, the velocity profiles were compared at three instants with an increasing freestream velocity for the SHS surface. Noted by the red horizontal line, the droplet height is always smaller than the boundary layer thickness for both the laminar and the turbulent state. When the freestream velocity $U$ is relatively small, the PIV measured the velocity profile almost adapts with the laminar boundary layer profile. As expected, higher $U$ would make the measured velocity profile follow the prediction of the turbulent boundary layer profile. It is noticed that once the transition process occurs, the measured instantaneous velocity profile would fluctuate a lot. The velocity profile hardly agrees with either the laminar boundary layer profile or the turbulent boundary layer profile (as shown in the instant of 3.67 s). Similar phenomena have been observed for droplets with different volumes and on surfaces with varying wettabilities.

![Figure 5.7. Comparison of velocity profile in front of the droplet on the SHS surface with droplet volume equal to 5 uL](image)

Provided the droplet profile and the evolution of the freestream velocity, the aerodynamic force $F_{aero}$ could be calculated by using the measured velocity profile, the theoretical laminar boundary layer profile and the turbulent boundary layer profile. As shown in Figure 5.8, the aerodynamic drag forces were presented using the three velocity profiles. The experimentally calculated drag force firstly agrees with the drag estimated with the laminar boundary layer. As the transition process happens, the experimental drag would fluctuate.
between the laminar and the turbulent drag force. This phenomenon indicates that the flow condition is essential in the prediction of the droplet aerodynamic drag.

Figure 5.8. Comparison of drag force variation between experimental and theoretical results.

(a) SHS surface with Vol = 5uL, (b) PC surface with Vol = 5uL

5.4.3 Force Balance on the Droplet

Figure 5.9. Force balance on 50uL droplet on different surfaces
During the droplet incipient motion, the fluctuating wind speed will generate fluctuating aerodynamic force, which leads to a fluctuating droplet profile. Since the droplet adhesion force is closely related to the contact angles, the adhesion force will also fluctuate with the wind. Figure 5.9 presents the force variations for the 50uL droplet over the PC, PDMS and the SHS surfaces. The upper row shows the timing of the critical wind speed while the lower row shows the force evolution of the droplets. Once the droplet starts to move, the corresponding drag force is always no smaller than the adhesion force. Both the drag force and the adhesion force increases with the wind speed, which means that after the adhesion force reaches the critical value, the adhesion force can further increase with wind speed. Droplet will comfort its shape with the aerodynamic force in order to make the adhesion force comparable to the drag force. It should be noted that the droplet motion could be started when the adhesion force has a sudden decrease, which means there might not exist a consistent critical velocity for the same test condition. In addition, the force result has been filtered and the force amplitude has higher fluctuation.

5.4.4 Critical Velocity Prediction

![Prediction of critical wind speed](image)

*Figure 5.10. Prediction of critical wind speed*
By analyzing the droplet displacement variations, the critical wind speed $U_{\text{crit}}$ can be measured directly when changing the droplet volumes. The critical speed can also be theoretically predicted according to the model mentioned in this study. Figure 5.10 presents the $U_{\text{crit}}$ results for PC, the PDMS surface and the SHS. The smaller the droplet volume is, the larger the critical wind speed is for all the three surfaces. The more hydrophilic the surface is, the higher the critical wind is to move the droplet. Critical wind speeds for different surfaces have a nonlinear relation with the changing droplet volume, which can be fitted into a power trend line. The indices range from -0.19 to -0.13, which is different from the $-1/3$ index mentioned by Roisman et al (2015). This is majorly due to the application of the Young-Laplace fit and the drag force calculation. Other reasons might include the difference in the experimental setup, where the distance to the leading edge is not the same.

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{figure5.11.jpg}
  \caption{Effect of boundary layer thickness}
  \end{figure}

According to Figure 5.10, the theoretical prediction of the critical wind speed agrees well with experimental results. Using the parameters from the PDMS, Figure 5.11 shows the critical wind speed calculated for different volumes and different distances to the leading edge. The critical wind speed could change significantly with the distance to the leading edge, especially for small droplet volumes. As the droplet moves to the downstream, the critical wind
speed could increase gradually, which means the droplet could stop in the downstream if the wind speed has an upper limit.

5.5 Conclusion

The critical wind speed which can start the incipient motion of a sessile droplet was experimentally measured. PIV technique was applied for the measurement of the velocity field around the droplet. With the detailed velocity information around the droplet and the droplet profile, the aerodynamic force and the adhesion force were calculated. The force balance for the droplet incipient motion was validated in order to use the theoretical model to predict the critical wind speed. The experimental and theoretical critical wind speed agreed with each other.

It was found the transition process on the flat plate could influence the determination of the critical wind speed. Wind speed fluctuation inside the boundary layer could lead to the profile fluctuation of the droplet. The shape variation of the droplet could result in the fluctuation of the adhesion force, which might give rise to the incipient motion once the aerodynamic force is larger. The critical wind speed had a power relation with the droplet volume, and the power indices range from -1.9 to -1.3 for current surfaces in this study. It turns out that the distance to the leading edge could significantly influence the critical wind speed especially for smaller droplets.

References


CHAPTER 6
AN EXPERIMENTAL INVESTIGATION OF A WIND-DRIVEN WATER DROPLET OVER THE SLIPPERY LIQUID INFUSED POROUS SURFACE

Liqun Ma, Hui Hu
Department of Aerospace Engineering, Iowa State University, Ames, Iowa, 50011

Abstract

The promising anti-icing performance of the slippery liquid infused porous surface (SLIPS) has been recently demonstrated for various engineering applications. The runback icing for aircraft and wind turbines could be effectively mitigated considering the timely removal of a water droplet by the wind shearing force due to the low adhesion on the SLIPS. In this study, the flow field both inside and around the wind-driven droplet over the SLIPS was experimentally investigated by using Particle Image Velocimetry (PIV) technique. Previous studies majorly focus on the internal flow pattern before the droplet incipient motion. In this study, the flow field inside a moving droplet was firstly investigated. As a result of the low surface adhesion of the SLIPS, droplet oscillations were eliminated and the droplet internal flow field could be corrected from the optical distortion. Besides the discussion on the wind speed, the droplet viscosity was also studied by varying the water concentration of the glycerin-water solution. It was found that the internal circulation was highly related to the droplet viscosity. The inner circulations within the water droplet would be mitigated when the droplet viscosity was increased. It was suggested that the internal flow should be considered when theoretically modeling the wind-driven droplet movement over the SLIPS. This study could provide experimental evidence for a broader application of the SLIPS in the icing-related industrial world.
6.1 Introduction

The motion of wind-driven droplet on surfaces is of fundamental importance to understand the runback icing phenomenon that occurs on airplane airfoils (Gent et al. 2000; White and Schmucker 2008), wind turbine blades (Parent and Ilinca 2011) and bridge cables (Kleissl 2010). During the runback ice accretion, the water droplets impinge on the surface and liquid water runs back from the impingement zone. These runback water would freeze over the surface if they fail to timely shed off from the surface by the wind shearing force, gravity force or centrifugal force. In this case, clear frozen rivulets would be generated and the ice shape always spread with large chordwise extent. Such runback ice accretion is a common problem for thermal anti-icing systems when the heating elements are only applied to the leading edge region. (Broeren et al. 2005) In some cases, the leading edge icing could be entirely prevented while the runback icing would be severely promoted. The formation of the runback icing aft the heated region was found to cause a considerable increase of drag. (Gray and Von Glahn 1953) This problem could be solved by optimizing the heating element distribution and utilizing surface coatings with low water adhesion force to mitigate the accretion of the runback icing. (Antonini et al. 2011)

The idea of using surface coatings with low water adhesion force is to allow timely removal of runback water by external forces before water freezes. Water adhesion force is usually characterized by the contact angle hysteresis (CAH) which is the difference between the advancing and the receding contact angle. Surfaces with low CAH usually use two strategies to reduce adhesion. One strategy is using hierarchical structures to trap air between the water droplet and the solid surface. These surface coatings are usually superhydrophobic surfaces (SHS) and they are inspired by the lotus leaf. Deposited water would stay a Cassie-Baxter state on SHS and the interaction between the water droplet and the solid surface is
minimized. The other strategy is maintaining a liquid lubricating layer between the water droplet and the solid surface. These surfaces are always called slippery liquid infused porous surface (SLIPS) and they are inspired by the *Nepenthes* pitcher plant. A water-immiscible lubricating organic liquid was trapped in the surface textures to have a molecularly smooth surface with low water contact angle hysteresis. (Wong et al. 2011) Even though both SHS and SLIPS could have deposited water droplet easily removed by the external force, SLIPS has at least two inborn advantages over the SHS. Firstly, the water repellency of SLIPS is pressure stable while the SHS can hardly stand up to pressure when the air cushion within the hierarchical structures is penetrated by water (Cassie-Baxter state to Wenzel state). Secondly, the SLIPS has better mechanical durability than the SHS since the textured solid surface is prone to irreversible defects caused by mechanical damage or fabrication. As a result, the SLIPS has more potential to be widely applied to engineering for ice protection systems.

Design and optimizing of ice protection systems using SLIPS would be highly depended on the knowledge wind-driven droplet motion on the SLIPS. As a novel surface invented within the current decade, interactions between the water droplet and the SLIPS has been studies for droplet bouncing (Hao et al. 2015), droplet impact dynamics (Muschi et al. 2018) and gliding droplet on an inclined surface (Keiser et al. 2017). Wind-driven droplet motion over the SLIPS has not been systematically studied. Besides the early wind-driven droplet models (Rothmayer and Tsao 2001; Dimitrakopoulos and Higdon 2003) when a hydrophilic surface was applied, recent studies compared wind-driven droplet motions on surfaces with different wettabilities experimentally (Moghtadernejad et al. 2013; Mandal et al. 2015). Most of these studies model the wind-driven droplet by balancing the aerodynamic drag and the droplet adhesion force. The water droplets are always assumed to be rigid bodies in
these models. In reality, inner circulation often exists for water droplets subject to moving ambient air. The interaction between the inner liquid flow and the outer air flow for a wind-driven moving droplet has not been experimentally investigated. The inner flow of the droplet is difficult to achieve due to the droplet oscillation (Milne 2013) during the wind-driven process. The internal flow could be significantly impaired by the unsteady optical refraction (Minor et al. 2007) caused by the droplet surface oscillation. Wind droplets moving on the SLIPS seems to be immune to the severe surface oscillation due to its small water adhesion force. Using SLIPS to measure the wind-driven droplet inner flow along with the outer flow could provide clues on how to modify the current theoretical model to improve its accuracy.

In this work, the wind-driven droplet movement over the SLIPS is experimentally investigated. Two PIV systems were used to measure the flow field inside and outside of the droplet simultaneously. The image distortion correction method was deployed on raw PIV images of the internal flow to achieve the valid velocity vectors in the vertical symmetric plane of the droplet. With the substrate mounted with the same SLIPS material, the droplet viscosity has been changed by adjusting the concentration of the glycerin-water solution. We discussed the droplet moving speed influenced by droplet volume, droplet viscosity and wind speed moving velocity with the droplet internal flow thoroughly considered. The experimental work presented here is believed to provide more details to establish a theoretical model which can predict the wind-driven droplet motion on the SLIPS.
6.2 Experimental Methods

6.2.1 PIV Measurement

A schematic of the PIV measurement setup is shown in Figure 6.1. An open circuit low-speed wind tunnel was used to provide the upcoming flow. The wind tunnel outlet shown in Figure 6.1 had a dimension of $W \times H = 8'' \times 5''$. An acrylic plate with a dimension of $W \times L \times T = 5'' \times 10'' \times 0.5''$ was fixed on a lab jack in order to adjust its upper surface to the same level with the bottom of the wind tunnel outlet. The leading edge of the substrate was 45° chamfered and a 10 mm gap was maintained in order to reduce the boundary layer’s effect from the wind tunnel. With such an alignment, the free stream wind speed over the substrate could be controlled from 0 to 20 m/s by adjusting the motor speed. During the test, the droplet was located about 15 mm downstream of the substrate leading edge and centered about the wind tunnel outlet to achieve a 2D outer flow condition.

In this study, two PIV systems were used to simultaneously measure the flow field inside and outside of the droplet. Two Fastcam Mini WX100 cameras (Photron) were connect

Figure 6.1. Schematic experimental setup for PIV measurement
to a computer with a switch (Netgear). The internal and outer flow field were respectively illuminated by two double-pulsed Nd:YAG laser (Newwave Gemini 200), which emits laser pulses of 200 mJ at the wavelength of 532 nm. The internal flow was seeded using the carboxylate-modified microspheres (FluoSpheres), which is 1.0 μm in diameter and has a Nile red fluorescent emission light at the wavelength of 575 nm. As shown in Figure 6.1, Camera 1 captures the internal flow with a longpass filter (Edmund) with cut-on wave length equal to 550 nm. Laser head 1 illuminates the internal flow from downstream of the flow to avoid surface reflection. The outer flow was seeded with ~1μm oil droplets generated by a smoke generator (Rosco). Camera 2 captures the outer flow field with laser head 2 illuminating downward to the substrate. The cameras and the laser systems were synchronized by two pulse generators (Model 565, BNC). The frequency of the laser pulse pairs was 15 Hz. The time duration for a pulse pair was varied according to the flow rate of the particles (internal flow: Δt = 2 ~ 20 ms, outer flow: Δt = 6 ~ 25 μs). In addition, laser pulses for the outer flow field were scheduled right between the two laser pulses measuring the inner flow. Timing of the camera exposure was controlled so that there existed no confliction between the two laser systems and only the right pulses could be captured. The internal flow field was measured using a 12× zoom lens system (LaVision). The measurement window was 10 × 5 mm and the corresponding image size was 2048 × 1024 pixels. The outer flow was measured using an AF Micro-Nikkor 105mm f/2.8D lens (Nikon) and the measurement window is 20 × 10 mm with the same image size. In addition, when studying the droplet velocity, the droplet motion was imaged by the shadowgraph technique with the background light supplied by a white studio light (Dot Line RPS Studio CooLED 200).
6.2.2 Surface and Droplet Preparation

![Figure 6.2. The viscosity of aqueous glycerol solutions under different temperatures. (Segur 1953)](image)

The SLIPS coating had a commercially available porous layer (Sterlitech®) which was made by a random network of Teflon nanofibrous membranes. The hydrophobic membrane was laminated. Its functioning surface had an average pore size of $\geq 200\text{nm}$ and its polypropylene backer was glued to the acrylic plate. The lubricating fluid used for the experiments was DuPont Krytox 103, which was one kind of clear, colorless perfluorinated oil used by Wong et al. (2011) and Liu et al. (2015). The slippery oil infused surfaces had a thickness of 60-80 $\mu$m, while the oil layer is maintained without quantitatively controlling its amount. No excess oil would drip from the surface when the substrate is tilted in this study.

During this study, the droplet was released using a Pipette for each run and the droplet volume was 20 $\mu$L. This volume was selected to mitigate the influence of the lubricant thickness, which could bring in issues from the lubricant dynamics (Kreder et al. 2018) if the droplet size is comparable. The droplet viscosity was changed by tuning the concentration of the glycerin-water solution. We assume the added fluorescent particles would not influence the droplet viscosity significantly. As shown in Figure 6.2, when changing the concentration of
the glycerin from 0 to 100%, the droplet viscosity could be changed from 1 to 1000 centipoise at 20 °C (Segur 1953). According to Figure 6.2, the droplet viscosity is highly related to temperature. We used the viscosities at 20 °C in this study considering the relatively constant room temperature during the test. According to Takamura et al (2012), the surface tension of aqueous glycerol solutions against the low viscosity oil would decrease with the increase of the glycerol concentration. This study focuses on the overall wind-driven droplet behavior and the flow field around and within it, while wetting details during sliding is not discussed due to the depletion of the lubricant and the randomness of the substrate texture. (Schellenberger et al. 2015; Smith et al. 2013)

6.2.3 Image Processing

In this study, the droplet shape could be subtracted from the raw images of PIV measurement. For each pulse of the laser sheet, the fluorescence particles inside the droplet could be illuminated simultaneously. The illuminated droplet appears as a brighter region compared with the dark background, which can be easily separated from the raw image using a custom MATLAB code. The raw image was firstly binarized and pixels representing irrelevant particles were removed due to their low connectivity level. The substrate would appear as a straight bright line in the raw image and the boundary of the substrate was detected by manually inputting its position. Holes in the droplet region were then filled so that the droplet could be recognized as a solid region and its boundary line could be detected. The advancing and receding points were defined as the intersection points between the substrate boundary line and the droplet boundary line. The advancing and receding contact angles are calculated by finding the tangent line across the advancing and the receding points for the second order fitted droplet boundary curves.
Due to the spherical shape of the droplet, illuminated particles are subject to refraction as the light ray traverses from the object plane (x-y plane) to the image sensor. Such optical distortion needs to be restored in order to achieve the correct internal flow field. In this study, we follow a similar method used by Kumar at al. (2017) to correct the raw images used for PIV measurement. As shown in Figure 6.4, we used a digitally distorted image from Minor at al. (2007) to test the Matlab script we developed according to the method (Kumar et al. 2017) as shown below.

According to the Snell’s Law of refraction, the incidence angle $\psi_d$ and the refraction angle $\psi_a$ are related as:

$$n_d \sin \psi_d = n_a \sin \psi_a,$$

where $n$ denotes the refraction index and the subscript $d$ and $a$ denote the drop and the air, respectively. Particularly, the incident angle $\psi_d$ is the angle between the local surface normal vector $\mathbf{n} = (n_x, n_y, n_z)$ and the image sensor normal vector $-\mathbf{k}$.

$$\cos \psi_a = \mathbf{n} \cdot (-\mathbf{k}).$$

Introduce a mapping function $\mathbf{M} = (M_x, M_y, M_z)$, such that

Figure 6.3. The 2D geometry of the droplet with particles illuminated in the x-y plane. The light path from the particle noted as P to the camera has been displayed.
\[ M = -k - \tan(\psi_a - \psi_d) \frac{k \times (n \times k)}{[k \times (n \times k)]}, \] 

(6.3)

and each component in \( M \) can be represented as

\[ M_x = -\tan(\psi_a - \psi_d) \frac{n_x}{\sqrt{n_x^2 + n_y^2}} \]
\[ M_y = -\tan(\psi_a - \psi_d) \frac{n_y}{\sqrt{n_x^2 + n_y^2}} \]
\[ M_z = -1 \] 

(6.4)

As a result, given the pixel location \((x_s, y_s)\) in the distorted image, the undistorted pixel location \((x_0, y_0)\) could be expressed as:

\[ x_0 = x_s - \frac{M_x}{M_z} z_s, \]
\[ y_0 = y_s - \frac{M_y}{M_z} z_s. \] 

(6.5)

(6.6)

Note that \( z_s \) is the corresponding \( z \) coordinate of \((x_s, y_s)\) on the reconstructed of the 3D drop surface. During the 3D surface reconstruction process, we assume each horizontal section has a shape like a circle, namely, the 3D surface is reconstructed by rotating the 2D droplet profile along with the vertical axis through the droplet center point. Similar to the study by Minor et al. (2007), the 2D surface profile (as shown in Figure 6.3) is given by

\[ \zeta(\theta) \approx R + b \cos \theta, \] 

(6.7)

where \( R \) is the baseline radius and the droplet height is \( H = R + b \). The equation of the 3D surface can be achieved and thus the surface normal can be calculated.
Figure 6.4. The image correction for optical distortion.

(a) Image with synthetic distortion field from Minor et al. (2007). (b) Image reconstructed from (a). (c) Recorded droplet image (after centered) with the droplet profile. (d) Distortion corrected image from (c).

The correctness of the distortion correction method in this study is demonstrated in Figure 6.4. By applying the distortion correction method to a synthetic distortion image generated by Minor et al. (2007) shown in Figure 6.4 (a), the corrected image result is achieved as shown in Figure 6.4 (b). The total size of the original image is 575×697 pixels and the regular grid has unit cells of 70×70 pixels. The droplet profile is provided as $R = 222$ pixels and $b = 353$ pixels. The indices of refraction for the droplet and air respectively are 1.33 and 1. (Minor et al, 2007) After correction, the regular grid has been recovered from the warped grid due to refraction in Figure 6.4 (b). However, it should be noted that the information near the droplet edge is deficient due to the critical local refraction condition. Especially for the droplet bottom region, no information could be achieved after correction as long as the contact angle is larger than 90°. All these facts indicate that neither the interaction with the outer flow
field nor the substrate surface’s immediate influence to droplet internal flow field could be accurately revealed by using the current experimental method. Despite the inaccessibility of the flow field along the droplet edge, it is demonstrated that most of the droplet center region could be recovered by the current distortion correction method.

When calculating the flow field inside and outside of the droplet, new sets of images are generated in order to fix the droplet in the new images’ center, which is achieved by recognizing the moving droplet’s front and back edge positions. By centering the droplet in the new test images, the internal flow relative to the droplet could be easily corrected and time averaged since the spatial information has been uniformed. Figure 6.4 (c) provides the droplet image where the droplet has already been centered. After manually detecting the two end points of the baseline and the droplet apex point in the first droplet-centered image, the baseline radius $R$ and the droplet height $H$, along with the droplet profile could be calculated according to Equation 6.7. We found that the calculated profile in this study could reasonably agree with the droplet shape throughout the following sequence of the centered droplets. As shown in Figure 6.4 (c), the actual droplet shape might not be axial symmetric but the deviation is so insignificant and we suggest the current profile equation is suitable for the droplet shape prediction over the SLIPS. According to Figure 6.4 (d), except for the expended particles within the near edge region, the recovered particles in the center region has similar quality with the initial raw image, which is suitable for the calculation of the flow field for the PIV measurement.
6.3 Results and Discussions

6.3.1 Droplet Movement on the SLIPS

![Graph showing droplet movement and wind speed](image1)

*Figure 6.5. Displacement of the droplet contact points and the wind speed.*

In this study, the droplet’s transient displacement was diagnosed by analyzing the movement of the contact point information. As shown in Figure 6.5, as the free stream wind speed increases from 0 to 5 m/s, the droplet approximately maintains a linear motion. Note that the critical wind speed which dislodges the droplet during the incipient on the SIIPS is hard to determine, which is due to that the liquid-liquid interface has made the droplet more mobile. However, the droplet has a smooth movement and the moving speed could be determined by calculating the slope of the linear fitting line for the displacement curve.

![Graph showing variation of contact angle](image2)

*Figure 6.6. Variation of contact angle on SLIPS.*
By analyzing the contact angle for the advancing contact point and the receding contact point, the variation of the dynamic CA during droplet motion corresponding to Figure 6.5 is shown in Figure 6.6. It is observed that the variation of the dynamic CA is also smooth and the CAH is below 10°, which means a small adhesion force exists for the moving droplet. It should be mentioned that the smooth dynamic CA variation indicates that the change of the droplet shape during the movement is negligible, and thus the optical distortion resulted from the droplet fluctuation could be neglected. In our preliminary results, it is observed that the CAH is related to the wind speed. Consequently, the adhesion force plays an important role to balance the aerodynamic force, which maintains the smooth movement of the droplet.

![Figure 6.6. Variation of droplet moving speed with changing wind speed for different droplet viscosities (percentage of water in %).](image)

*Figure 6.7. Variation of droplet moving speed with changing wind speed for different droplet viscosities (percentage of water in %).*

By measuring the averaged droplet moving speed, it was found that both wind speed and droplet viscosity influence the wind droplet movement. As shown in Figure 6.7, droplet moving velocity has a power relation with wind speed. Different droplet viscosities would result in similar power indices when the water percentage is large and the viscosity seems to
have insignificant influence on the droplet speed when the percentage of water is larger than 40%. However, with an increasing droplet viscosity, the droplet moving speed decreases and it is harder for droplets to reach a higher moving velocity for the pure glycerin liquid.

![Graph showing variation of droplet moving speed with changing droplet viscosities.](image)

*Figure 6.8. Variation of droplet moving speed with changing droplet viscosities.*

As shown in Figure 6.8, the viscosity’s effects are further investigated. A general trend is observed that when the viscosity is smaller than 10 centipoises, droplet velocity seems to be irrelevant to the droplet viscosity; the droplet moving speed would decrease if the droplet viscosity is continuously increased. Wind speed appears to have no significant influence on the general trend influenced by the viscosity. This phenomenon indicates that the wind-driven droplet motion mechanism could be fundamentally altered when the droplet viscosity is increased.
6.3.2 Velocity Field for the Wind-Driven Droplet

![Speed Contour](image)

Figure 6.9. Time averaged velocity field inside and outside of the 100% water droplet. The contour of the velocity magnitude with velocity vector fields overlapped.

The averaged flow field around the moving water droplet is provided in Figure 6.9 with the corrected internal flow field overlapped. The free stream flow comes from the left and blows to the right. The flow field has been fixed relative to the center of the droplet. At least 100 frames of the PIV velocity field were averaged. It is noteworthy that the scale of the flow speed for the outer flow and the internal flow are different. Outer flow is of an order of 1000 larger than the internal flow. These results do not necessarily indicate that the internal flow did not reach the no-slip condition at the droplet surface. It is because that current experimental setup could not achieve the inner interface velocity information due to the optical correction process. The internal circulation observed in Figure 6.9 indicates that the droplet’s internal
circulation might challenge the rigid body assumption when analyzing the force balance over it to predict the droplet moving speed.

Figure 6.10. Time averaged horizontal velocity profiles near the droplet.
(The droplet volume is 20 μL and the freestream wind speed $U_{\infty}$ is 3.9 m/s)

\(\nabla\) (80% water), \(\square\) (60% water), \(\diamond\) (40% water), \(\blacklozenge\) (20% water)

With a fixed freestream wind speed as $U_{\infty} = 3.9$ m/s, the time-averaged velocity profiles of the outer flow fields are compared at different streamwise locations regarding the wind-driven droplet. As shown in Figure 6.10, droplets with different viscosities turn out to have limited influences on the outer flow field when they have the same volumes. The existence of the droplet has changed the upstream boundary layer’s velocity profile into the downstream wake velocity profiles. Note that at locations of -0.5D, 0D and 0.5D, velocity information overlapped with the droplet is regarded as zeros according to the PIV result. It seems that the droplet viscosity could influence the downstream velocity profiles very close to the droplet (as shown in Figure 6.10 at locations downstream of -0.5D). Results show that the smaller the droplet viscosity is, the larger the velocity deficit could be behind the droplet. This phenomenon indicates that droplet with smaller viscosities could have caused more energy loss of the upcoming wind according to the law for the conservation of energy.
Figure 6.11. Time averaged velocity field inside the 20 μL droplet when the wind speed is 3.9 m/s. The contour of the velocity magnitude with velocity vector fields overlapped. (a) 80% water. (b) 60% water. (c) 40% water. (d) 20% water.

The internal flow field for droplets with different viscosities are compared in Figure 6.11. Compared with the outer flow field which has small difference as shown in Figure 6.10, the magnitude of the internal flow field has changed significantly for different droplet viscosities. Along with the 100% water droplet case presented in Figure 6.9, it is obvious that the smaller the droplet viscosity is, the larger the internal circulation’s magnitude is. This is evident when comparing the maximum values of the color bars. Since the internal circulations are calculated relative to the droplet’s position, we can conclude that the wind-driven droplet is moving downward from the SLIPS neither by sliding nor by rolling, but by moving with internal circulation. This phenomenon is quite different from previous studies when the droplet is driven by gravity (Thampi et al, 2013; Smith et al, 2013). New dynamics could be introduced for the wind-driven droplets if the internal flow needs to be considered.
Figure 6.12. Distribution of the horizontal component of the inner flow field at the vertical line across the circulation center for different droplet viscosities. (a) Inner flow fields velocity profiles. (b) non-dimensional velocity profiles.

Figure 6.12 compared the horizontal component of the internal flow velocity at the vertical line across the droplet circulation center at different viscosities. Figure 6.12 (a) presents the curves with units and Figure 6.12 (b) provides the non-dimensional results. Under the same wind speed of 3.9 m/s, the intensity of the internal circulation is decreasing when the droplet viscosity increases. Larger viscosity would lead to a higher resistance to the inner circulation and as thus a slower inner circulation is generated. As shown in Figure 6.12 (b), we use the Ca number to generalize the inner circulation’s velocity profiles. The capillary number represents the relative effect of viscous drag force versus surface tension. According to Segur (1953), the glycerin solution could change its surface tension from 65.26 dynes/cm to 71.68 dynes/cm (20 °C) in this study. Results have shown that droplets with water percentage from 40% to 100% almost collapse. Results with more viscous solutions are not provided. It should be noted that the viscosity value is much more sensitive to the glycerin’s concentration when water percentage below 20% compared with others. the droplet moving speed for these cases are very close to the magnitude of the internal flow. The inaccurate determination of the droplet position could significantly influence the inner velocity distribution. It could be assumed that
for the non-dimensional results as presented in Figure 6.12 (b), improved measurement accuracy could have the curves from different cases collapse better.

6.4 Conclusion

Flow fields both inside and around a wind-driven droplet over the SLIPS were measured using the PIV technique. By centering the moving droplet in a new set of images and correcting the distorted particle images, the flow field of the wind-driven droplet moving on the SLIPS was systematically investigated. The influence from the wind speed and the droplet viscosity was discussed regarding the droplet speed. It was found that different from the gravity-driven droplet motion, there exist internal circulations of the wind-driven droplet, which indicates that the dynamics of the droplet motion could be very different and the internal flow should be taken into consideration. By quantitatively investigating the flow field inside and outside of the droplet, it was found that the inner flow and the outer flow were of a different order of scales for the speed magnitude. In addition, droplet viscosity plays an important role in the inner flow pattern, that is, the larger the droplet viscosity is, the slower the internal circulation would be.

References


CHAPTER 7
GENERAL CONCLUSION

7.1 Major Accomplishments of the Current Research

A novel wind tunnel to accelerate the droplet was developed and the droplet impact Weber number had been increased to 3000. In this study, the vertical wind tunnel simulated the flow impact onto a flat plate in its test section. It was different from most of the traditional wind tunnels since the wind would be diverged at the test section and then converged at a suction ducted fan. We achieved the high-speed images for the droplet impact dynamics on various bio-inspired icephobic surfaces, and the impact velocity has been significantly increased compared with most previous studies when free falling droplets were used. Droplet impact dynamics are firstly compared for the SHS, SLIPS, feather and hydrophilic surfaces under higher impact velocities.

Droplet impact dynamics onto a soft PDMS gel surface was experimentally investigated using the novel wind tunnel aforementioned. A rebound-splashing phenomenon was reported, and it turned out to be a soft-surface featured phenomenon which has not been reported previously. A theoretical model based on the surface deformation was developed to determine the criterion parameters which can predict the rebound splashing phenomena. The icephobicity of the soft surface was finally validated on the airfoil model in an icing wind tunnel. The soft surface appeared to be a promising icephobic surface which could be applied on aircraft ice mitigation.

The durability of the SHS and the SLIPS was experimentally investigated using a newly generated high-speed spray generator. Micro-scaled droplets were accelerated by a metal ducted fan, and the spray impact velocity could be controlled from 0 to 100 m/s. Surface
wettability and surface morphology were compared with different spray erosion durations. A wettability based lifetime model was developed following the Cumulative-Fatigue-Damage theory. It was quantitatively demonstrated that the SLIPS had better performance than SHS in terms of durability regarding aircraft icing.

PIV measurement was conducted to measure the flow around a wind-driven droplet on solid surfaces with various wettabilities. It was found the motion of the droplet was controlled by the force balance between the aerodynamic force and the surface adhesion force. A theoretical model based on the force balance analysis was developed to predict the critical wind speed during the incipient droplet motion. It was concluded that the velocity profile within the boundary layer could significantly influence the aerodynamic forces over the droplet.

An experiment on the wind-driven droplet moving on the SLIPS surface has been investigated. Both the flow around a moving droplet and the droplet’s internal flow have been quantitatively measured using the PIV technique. The optically distorted internal particle images have been corrected before the PIV correlation process. It was found that the wind-driven droplet has an internal circulation flow when moving downstream, which is different from the gravity-driven droplets on the inclined surfaces.

7.2 Recommendations for Future Research

The research work in this study involves a lot of cutting edge physics problems, and lots of newest knowledge from recent publications could promote a better understanding of the underlying mechanisms. Based on that fact, the following recommendations were suggested to guide the current work to the next station:

1) Droplet impact dynamics could be investigated under lower temperatures by locating the wind tunnel inside a walk-in cooler. Although the droplet impact velocity has been increased to a level closer to the aircraft icing condition, current studies only studied the impact
dynamics under room temperatures. Impact dynamics under subzero temperature condition would provide more immediate information for research in aircraft icephobic coatings.

2) Droplet impact dynamics onto soft surfaces need to be further investigated by measuring the detailed droplet-surface deformation process. The newly discovered droplet rebound-splash phenomenon is believed to be a result of the elastic deformation of the soft surface. A time-resolved, quantitative surface deformation measurement could provide more insight to understand the mechanisms underlying the rebound-splash phenomenon.

3) Coating durability test could be extended from spray erosion to ice crystal erosion by adding a cooling facility which could convert water spray into ice crystals. Aircraft icing is more usually subject to supercooled water droplet and ice crystal erosion. Such an upgrade would make the durability test more persuasive to validate the surface icephobicity for inflight aircraft scenarios.

4) Wind-driven droplet movement could take the 3D droplet surface profile into consideration. The current theoretical model assumes the droplet has an axisymmetric shape while using the actual droplet geometry will refine the details for critical velocity prediction. Digital image projection technique could be applied while the spatial resolution and shadow effect of the droplet cap might cause problems especially for measurement on hydrophobic surfaces.

5) The internal flow of wind-driven droplet was a 2D measurement since the flow was illuminated by a laser sheet. However, considering the 3D droplet shape and the non-uniform flow around the droplet, the droplet’s internal flow should have 3D complexities. Future research could try to cope with the 3D velocity field measurement within the wind-driven
droplet. Tomo-PIV could be applied and a new algorithm considering the image distortion correction should be developed during the correlation process.