An Experimental Study on the Dynamics of Water Droplet Impingement onto Bio-inspired Surfaces with Different Wettabilities

Liqun Ma\textsuperscript{1}, Haixing Li\textsuperscript{2}, Hui Hu\textsuperscript{3}(\textsuperscript{[\+\++]})

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

The dynamics of water droplet impingement at high Weber numbers onto bio-inspired surfaces was experimentally investigated. Water droplets with an initial diameter of 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 were presented for different surfaces. The splashing phenomena appeared for all cases in these experiments. From 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. 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.

Nomenclature

\begin{itemize}
  \item CA = Contact angle
  \item D = Droplet diameter before impinging onto the substrate
  \item K = Constant related with droplet deposition and splashing
  \item $l_0$ = Characteristic velocity of the droplet wind tunnel
  \item Oh = Ohnesorge number
  \item Stk = Stokes number
  \item $t_0$ = Characteristic time of the droplet
  \item Re = Reynolds number
  \item We = Weber number
  \item $U_{\text{impact}}$ = Droplet impact velocity
  \item $U_0$ = Characteristic velocity inside the droplet wind tunnel
  \item $\mu$ = Dynamic viscosity of water
  \item $\mu_{\text{air}}$ = Dynamic viscosity of air
  \item $\rho$ = Density of water
  \item $\sigma$ = Surface tension
\end{itemize}

\textsuperscript{1} Graduate Student, Department of Aerospace Engineering.
\textsuperscript{2} Graduate Student, Department of Aerospace Engineering.
\textsuperscript{3} Professor, Department of Aerospace Engineering, AIAA Associate Fellow, Email: huhui@iastate.edu

Copyright © 2017 by Liqun Ma, Haixing Li and Hui Hu from Iowa State University. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.
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 aircrafts 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 adhered with ice. 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, 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. 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. Besides concerns for the extra payload and the potential 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 are also more efficient, economic 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. tested the icephobicity of the lotus-leaf-inspired superhydrophobic surface, finding the reduction of water surface contact area can retard the ice nucleation under a low humidity. Wong et al. 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 repellant too. Inspired by penguins which lived in the world’s coldest environment, Wang et al. 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 aircrafts 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 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 which is comparable to the cruise altitude of common commercial aircrafts. Srinivasan et al., Bormashenko et al. and Liu et al. analyzed the hydrophobicity of pigeon and duck feathers. They all concluded that the water repellency of the bird feather in general is 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 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. This paper investigated the high speed impingement dynamics of water droplets on the bio-inspired surfaces, seeking to provide insights for application of the novel surfaces for inflight aircrafts.

Droplet need 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 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. achieved high-velocity micro-droplets using the breakup of ultrafast liquid jets generated by laser-induced cavitation. Zhang and Liu 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 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 a fundamental insight into novel bio-inspired anti-icing strategies for aircraft, which will ensure a safe and efficient flight of aircraft in the future.
II. Experimental method

A. Experimental setup

In order to achieve higher impact velocities, a droplet wind tunnel was designed to accelerate the air surrounding the droplet. As shown in Figure 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). The background light was provided by a 20W LED spotlight 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 10¹ Hz and a minimum of 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 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.

B. 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 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 inflight breakup, which is a result from the process of the drastic aerodynamic acceleration 18.

Several design options are considered to make the droplet wind tunnel efficient and economic. Figure 2 presents four designs of the wind tunnel test section. Figure 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. The profiles of the test sections follow the streamlines around a finite flat plate and an infinite flat plate, respectively. The test section is bended 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 cooling system, to the wind tunnel from the bottom.
The major concern for the current design is that whether the symmetricity 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 \( (l_0/U_0) \). The characteristic time of the droplet is defined as:

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

when the water density \( \rho = 1000 \text{ kg/m}^3 \), droplet diameter \( D = 3 \text{ mm} \) and the air viscosity \( \mu_{\text{air}} = 1.81 \times 10^{-5} \text{ Pa·s} \), \( t_0 \) 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:

\[
\text{Stk} = \frac{t_0}{(l_0/U_0)}
\]

for 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.

### C. Test surfaces

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\(^4\) and the lotus-leaf-inspired superhydrophobic surface. Specimens of the feathers were natural goose feathers gathered from 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 3(a) presents the view of a droplet placed on the goose feather and Figure 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 3(a). It is believed that this hierarchical structure contributes to the hydrophobicity of the bird feather.\(^ {12-14} \) The SLIPS is provided by Professor Tak-Sing Wong at Pennsylvania State University. It is used as a reference to have a glance at the influence from 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.

![Figure 2. Comparison of different wind tunnel designs to accelerate an individual droplet](image)

Figure 2. Comparison of different wind tunnel designs to accelerate an individual droplet

![Figure 3. (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.](image)

Figure 3. (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.
D. Parameter space

![Parameter space diagram](image)

Figure 4. Parameter space of (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 4 presents the phase diagram of the test parameters during this experiment. Figure 4 (a) shows the relation between the Weber number and the impact velocity. The Weber number is defined as:

\[ \text{We} = \frac{\rho D U_{\text{impact}}^2}{\sigma}, \quad (3) \]

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

\[ \text{Re} = \frac{\rho D U_{\text{impact}}}{\mu}, \quad (4) \]

and the Ohnesorge number is defined as:

\[ \text{Oh} = \frac{\mu}{\sqrt{\rho \sigma D}}. \quad (5) \]

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

\[ \text{Oh} = \sqrt{\frac{\text{We}}{\text{Re}}}. \quad (6) \]

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 4 (b) is presented when \( K = \text{Oh Re}^{1.25} = 57.7 \), which is suggested as a boundary line for deposition and splashing 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.
III. Results and discussion

A. 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 5 presents the sessile droplet profiles on different surfaces tested in this experiment. The cubic spline is used to present the result in Figure 5 (a) and the profiles are measured from the sessile droplets which are provided in Figure 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 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 5 (b).

![Figure 5](image_url)

Figure 5. Comparison of contact angles on different surfaces. (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>
<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 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 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 with the moving speed of the contact line, which is not quantitatively controlled in these experiments. However, changing ranges of the advancing and receding CAs are provided, which can give a glance at the wettability for current test surfaces.
B. Effect of surfaces

Figure 6. Evolution of droplet impingement on different surfaces with Weber numbers around 1800.

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 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 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 as 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. 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.

C. Effect of Weber number

This section focuses on the Weber number’s influence to the evolution of the impingement process. Four Weber numbers were selected to present the results. In a similar fashion as Figure 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 7 and Figure 9, and large contrast ratio is used to present Figure 8 and Figure 10.

![Figure 7](image_url)

**Figure 7. Evolution of droplet impingement on the hydrophilic surface at different Weber numbers**

Figure 7 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, 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 8. Evolution of droplet impingement on the goose feather at different Weber numbers

Figure 8 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 with the direction of the grooves formed by the barbs (see the instant of 1.0 ms for the last columns and the instant of 2ms 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 break up 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.

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 9. 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 the stable state. Impingement 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 to 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 10. Evolution of droplet impingement on the superhydrophobic surface at different Weber numbers

Figure 10 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.

D. 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 11 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 11 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 20. 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 breakup once
its rim flow above them. It is expected that such obstacle induced breakup will happen on water films with thickness
larger than the critical thickness for capillary breakup. As noted by the arrows at 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 seems 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 become thinner and thinner in the center region,
capillary breakup appears as holes inside the water film (noted by 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 11 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 11 Detailed views of the droplet impingement on the goose feather when the Weber number is 3250](image-url)
The generalized mechanism for the four surfaces are also presented in Figure 12. A color gradient is applied to the water droplet and water film, where the darker color indicates a larger thickness. The gray streaks represents the barbs of the feather and the red triangles on the barbs represents the physical or chemical obstacles mentioned in Figure 11. A top view of the crown-like water sheet with secondary droplets distributed in the edge are 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 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 center 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 12. The spreading, receding and rebounding phenomena are presented using arrows. Impingement mechanisms with the highest Weber number for the SLIPS is not illustrated in this schematic, since the inner breakup process has similar features with the goose feather and the superhydrophobic surface.

Figure 12. Schematic mechanism of high-speed droplet impingement on different surfaces

IV. 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 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 from 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 breakup 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 together. 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.

Acknowledgments

The research work is jointly supported by NASA grant number NNX12AC21A, National Science Foundation under award numbers CBET-1064196 and CBET-1435590, and Iowa Space Grant Consortium Base Program for Aircraft Icing Studies. The authors also gratefully acknowledge the help of Dr. Tak-Sing Wong at Pennsylvania State University for providing SLIPS coatings used in the present experimental study.

References


American Institute of Aeronautics and Astronautics


