High-Speed Imaging to Quantify the Transient Ice Accretion Process on a NACA 0012 Airfoil

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Ice accretion on aircraft wings poses a performance and safety threat as aircraft encounter supercooled droplets suspended in the cloud layer. The details of the ice accretion depend on the atmospheric conditions and the flight parameters. The icing process on the wing consists of a complex interaction of water deposition, surface water transport, and freezing. The aerodynamics affect the water deposition, the heat and mass transport, and ice accumulation; meanwhile, the accumulating ice affects the aerodynamics. Until now, most experimental measurements of aircraft icing have focused on the final ice shapes formed after exposure for a set duration to icing conditions. This approach fails to capture the transient processes that form the final ice formations. Here, we present experiments conducted in the Iowa State icing wind tunnel on a NACA 0012 airfoil to study the transient ice accretion process under varying icing conditions. High-speed video of the icing process was acquired under controlled environmental conditions to quantitatively measure the transient water film run back, rivulet formation, and accumulated ice growth, and the experiments show how varying the environmental conditions modifies the ice accretion process.

I. Introduction

Ice accretion poses a threat to the safety and performance of aircraft in cold weather, especially as the aircraft travels through the cloud layer and encounters supercooled liquid water droplets. The ice formation depends on the flight conditions and environmental parameters,1 and much effort has been spent to predict icing conditions using theoretical and computational models.2–5 The Iowa State Icing Research Tunnel has been constructed to provide experimental data of aircraft icing conditions to inform the development of advanced icing models.

The ice forms a variety of structures as it forms on wings, and the details of the ice formation will vary with the environmental and operating conditions.6 When operating conditions are cold and the air has a small liquid water content (LWC), the water droplets freeze immediately upon impact with the wing, forming rime ice. At warmer air temperatures, just below freezing and with larger LWC, the water accumulating on the wing does not immediately freeze and mass transport along the surface of the wing can play an important role in the glaze ice formations and accretion.

During glaze ice formation, the deposited water droplets form a film of water and may form rivulets that run back along the chord.3 Instability of the accreting ice leads to the formation of surface roughness.7 The surface roughness elements can enhance the local heat transfer8 and disrupt the wing’s aerodynamic performance.9 The ice roughness elements that protrude out into the flow will capture impinging droplets faster and experience enhanced heat transfer compared to surrounding ice regions; therefore, protruding ice elements will grow faster than surrounding regions, amplifying ice roughness.10

Previous experiments have examined the accreted ice shapes and aerodynamic characteristics at specified fixed snapshots in time after the initial onset of icing (e.g.,11–14); however, this approach ignores the importance of the transient water run back process that can redistribute the impinging water on the wing before it freezes.15 The distribution of ice formations on the wing depend on the initial distribution of water; therefore, understanding the development of the ice accretion requires understanding the initial transient process.

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In this study, we perform icing wind tunnel experiments and capture high-speed videography of the ice accretion process on a NACA 0012 wing. Keeping the temperature, angle of attack, and liquid water content the same but varying the free stream velocity leads to differences in the ice accretion process. The recorded images are digitized to extract quantitative measurements of transient icing features during the icing process.

II. Experimental Methods

All experiments were performed in the ISU Icing Research Tunnel. The wind tunnel is a closed-loop type with a $25.4 \times 25.4 \text{ cm}^2$ test section. The tunnel is refrigerated via a heat exchanger installed after the wind tunnel fan. The heat exchanger is chilled by a 40 hp compressor (Vilter), and the operating temperature is set by a temperature controller that toggles the compressor on/off when the working temperature is above/below the setpoint. The wind tunnel can be cooled to $-20^\circ \text{C}$. A K-type thermocouple and thermocouple controller (Omega, HH501BJK) monitored air temperature in the test section before and after each test; however, ice build-up on the temperature probe during the experiments precluded reliable \textit{in situ} measurements. Icing conditions in the wind tunnel are generated by spraying finely atomized water droplets into the chilled air upstream of the test section. A diagram of the wind tunnel is given in Fig. 1.

![Diagram of the wind tunnel](image)

**Figure 1**: The Iowa State University icing wind tunnel is a closed return type wind tunnel. The heat exchanger for the refrigeration system is installed after the fan. Supercooled water droplets are generated with a pneumatic spray system that sprays atomized water into the refrigerated air stream prior to the contraction and test section.

The spray system consists of an array of three pneumatic atomizing spray nozzles (Spraying Systems Co., 1/8NPT-SU11) and pressure regulators to control the water line and air line pressures. The volume flow rate of water was monitored with a digital flow meter (Omega, FLR-1605A). Adjusting the pressure regulators on the air and water lines adjusted the mass flow rate of water; therefore, the liquid water content \( \text{LWC} = \frac{\text{mass of water}}{\text{volume of air}} \) could be set for each wind speed tested via pressure adjustments. Droplet size is controlled by the relative air and water pressures. The relationship between the liquid water content \( \text{LWC} \), the wind speed \( U \), and the volume flow rate of water \( \dot{V} \) (Eqn. (1)) assumes that the all of the sprayed water is evenly distributed over the test section area \( A \). The water density \( \rho \) relates the volume flow rate of water measured by the flow meter to the mass flow rate of water required by Eqn. (1). For each experiment, the volume flow rate of water was adjusted to achieve the desired liquid water content according to Eqn. (2). In all trials, the air pressure was set at least 10 psi higher than the water pressure to ensure the
generated droplets have a small mean volume diameter (15–100 μm).

\[ \text{LWC} = \frac{m_{\text{water}}}{V_{\text{air}}}, \]
\[ = \frac{\rho \dot{V}}{A \cdot U}, \]
\[ \dot{V} = \frac{\text{LWC} \cdot A \cdot U}{\rho}. \] 

The experiments were conducted using a 3D printed NACA 0012 profile test wing that spanned the width of the test section; thus, pseudo two-dimensional flow over the wing. The wing chord length \( c = 101.6 \text{ mm} \). Supported by a stainless steel rod, the wing was mounted at its quarter-chord and oriented horizontally across the middle of the test section. The angle of attack was adjusted by pivoting the wing about the rod and fixing it at the desired angle measured with a digital inclinometer. The wing was finished with a coating of primer and wet-sanded to a smooth finish using 1000 grit sand paper.

High speed video was recorded using a CMOS camera mounted 0.5 m above the wing (PCO Tech, Dimax) using a 60 mm macro lens (Nikon, 60 mm Nikkor 2.8 D). The camera was positioned normal to the wing chord, providing a top-down view with a 1500 x 480 pixels\(^2\) field of view and a pixel resolution of 11.74 pixels/mm. The camera was calibrated by placing a calibration target consisting of a grid of dots aligned in the plane defined by the wing span and wing chord and computing a planar homography using the direct linear transform method, thus mapping the pixel coordinates to real-space coordinates projected onto the wing plane. The captured images were dewarped using this homography prior to extracting physical features.

Low-flicker illumination was provided by a pair of 150 W fiber-coupled halogen lamps (AmScope, HL250-AS). The experimental configuration is illustrated in Fig. 2. Each trial consisted of 8828 images acquired at a frame rate between 30–300 fps. The frame rate for each trial was chosen based on the freestream velocity, with the lowest freestream speeds being acquired at 30 fps and the highest freestream speeds being acquired at 300 fps.

The experimental trails presented here were conducted at an air temperature of \( T = -8^\circ \text{C} \), freestream velocities \( U = 20, 40, \) and \( 60 \text{ m/s} \), and the liquid water content for each trail was \( \text{LWC} = 1.1 \text{ g/m}^3 \). The angle of attack was set at \( \alpha = -5^\circ \) to observe the icing process on the pressure side of the wing where the water film runback and rivulet formation is most prominent.

**III. Description of the icing process**

Icing occurs when supercooled water droplets suspended in the air are carried by the freestream and impact upon the body. The collection efficiency \( \beta \) specifies the distribution of water droplets impacting the body, and is largely determined by the relative size of the droplets compared to the body and inertia. Heavy droplets follow ballistic trajectories to impinge on the body, whereas the smaller, lighter droplets are more inclined to follow streamlines and may miss the body altogether. The droplet trajectories, and consequently the collection efficiency, is determined by the droplet inertia parameter

\[ K = \frac{\rho_w D^2 U}{18L\mu}, \]
where $\rho_w$ is the density of water, $D$ is the droplet diameter, $\mu$ is the air viscosity, and $L$ is a characteristic length of the body. For airfoils, this length $L$ may be taken as the radius of curvature of the leading edge. Once deposited onto the body, the water may then be driven by aerodynamic shear stress in a Couette flow before freezing. This aerodynamic driving force redistributes the water from where it was deposited to other regions of the body. Furthermore, the water film may break up into rivulets as it runs back, creating a 3-dimensional surface topology and affecting water collection and redistribution over the surface. The rivulet formation is governed by the interplay of surface tension forces and inertial forces, thus, the Weber number is an important parameter for determining the ice formation:

$$We = \frac{\rho U^2 L}{\sigma},$$

where $\rho$ is the air density and $\sigma$ represents the water surface tension. The ice accretes according to a mass balance of water phases deposited on the wing, freezing into ice, and running back, and according to a heat balance of the water releasing latent heat during phase transition and the cooling action of convection and conduction. Overall, the amount of ice that accretes relative to the size of the body is given by $a$, the accumulation parameter:

$$a = \frac{LWC \cdot U \cdot \tau}{L}.$$  

Here, $\tau$ is the duration of water and ice accumulation. Equation (5) relates the ice accumulation to the rate that airborn water is carried toward the body with characteristic size $L$.

We start by examining a typical ice accretion trial at $U = 40 \text{ m/s}$, and then examine the effect on the icing process as the freestream velocity is changed. The ice accretion process on the pressure side of the wing for $U = 40 \text{ m/s}$ and $\alpha = 5^\circ$ is given in Fig. 3. The ice accretion exhibits characteristics in agreement with previous works on icing. First, the impinging water forms a film at the leading edge (Fig. 3(a)). As the film flows back along the wing, rivulets develop with fairly regular spacing (Fig. 3(b)). Near the leading edge, the water film begins to exhibit roughness due to instability and water that was deposited ahead of the advancing water film can now be seen as nucleation points for feather growth in Figs. 3(c–d). As the roughness elements grow and the ice layer thickens, the extent of the liquid water film begins to retreat back towards the leading edge (Fig. 3(e)). The roughness elements in the ice form wake regions, whereby flow separation forms behind the thickening ice sheet and prevents water from impinging behind the ice sheet. Only the ice feathers which reach out into the outer flow continue to grow outward and into the oncoming outer flow (Figs. 3(f–g)). When sufficient water accumulates in the ice roughness, aerodynamic forces splash water and deposit it on the wing behind the accumulated ice (Fig. 3(h)).

At slower freestream velocities, the water film fails to break up into rivulets. In this case, the water impinges on the wing at the leading edge forms a film at the leading edge (Fig. 4(a)). A water film front forms (Fig. 4(b)), and water begins to bead up at the advancing film front; however, rivulets never develop by the time the water beads begin to solidify (Figs. 4(c–d)). Near the leading edge, the water film begins to exhibit roughness due to instability and the water beads continue to accumulate water and grow Figs. 4(e–f). Again, as the roughness elements grow and the ice layer thickens, the extent of the liquid water film begins to retreat back towards the leading edge (Fig. 4(g)), and the roughness elements in the ice form wake regions, whereby flow separation forms behind the thickening ice sheet and prevents water from impinging behind the ice sheet (Fig. 4(h)).

As the wind speed is increased to $U = 60 \text{ m/s}$, the mass flow rate of water impinging on the wing increases and the wind shear driving the water film flow increases in accordance with Eqn. (5). The water film very quickly breaks into rivulets which advance down the wing (Figs. 5(b–d)) and which have a smaller width and spacing than the slower freestream cases. Here, the rivulets exhibit narrower spacing between neighboring rivulets, and the rivulets advance further downstream. The downstream extent of the water film begins to freeze (Fig. 5(e)). Near the leading edge, the water film begins to exhibit roughness (Fig. 5(f)). As the roughness elements grow and the ice layer thickens, the extent of the liquid water film begins to retreat back towards the leading edge (Figs. 5(g–h)).

Here, high speed video of the ice accretion provides a qualitative view of the transient processes involved during icing, which lends some insight into the physics of ice formation. However, to study the icing process in detail, we require quantitative measurements of the ice features as the develop and evolve. We will now present some methods to extract ice feature measurements from the high speed video of the icing process.
Figure 3: The ice accretion process on the pressure side of a NACA 0012 wing with chord, \(c = 101.6\) mm, angle of attack, \(\alpha = 5^\circ\), freestream velocity, \(U = 40\) m/s, liquid water content, LWC = 1.1 g/m\(^3\) and temperature, \(T = -8^\circ\) C. First, the impinging water forms a film at the leading edge (Figs. 3(a)). As the film flows back along the wing, rivulets develop (Fig. 3(b)). Near the leading edge, the water film begins to exhibit roughness due to instability and the droplets that were deposited ahead of the advancing water film can now be seen as nucleation points for feather growth in Figs. 3(c–d). As the roughness elements grow and the ice layer thickens, the extent of the liquid water film begins to retreat back towards the leading edge (Fig. 3(e)). The roughness elements in the ice form wake regions, whereby flow separation forms behind the thickening ice sheet and prevents water from impinging behind the ice sheet. Only the ice feathers which reach out into the outer flow continue to grow outward and into the oncoming outer flow (Figs. 3(f–g)). When sufficient water accumulates in the ice roughness, aerodynamic forces splash water and deposit it on the wing behind the accumulated ice (Figs. 3(h)).
Figure 4: The ice accretion process on the pressure side of a NACA 0012 wing with chord, $c = 101.6$ mm, angle of attack, $\alpha = 5^\circ$, freestream velocity, $U = 20$ m/s, liquid water content, $LWC = 1.1$ g/m$^3$ and temperature, $T = -8^\circ$ C. In this case, the water impinges on the wing at the leading edge forms a film at the leading edge (Fig. 4(a)). A water film front forms (Fig. 4(b)), and water begins to bead up at the advancing film front; however, rivuletts never develop by the time the water beads begin to solidify (Figs. 4(c–d)). Near the leading edge, the water film begins to exhibit roughness due to instability and the water beads continue to accumulate water and grow Figs. 4(e–f). As the roughness elements grow and the ice layer thickens, the extent of the liquid water film begins to retreat back towards the leading edge (Fig. 4(g)). The roughness elements in the ice form wake regions, whereby flow separation forms behind the thickening ice sheet and prevents water from impinging behind the ice sheet (Fig. 4(h)).
Figure 5: The ice accretion process on the pressure side of a NACA 0012 wing with chord, $c = 101.6\, \text{mm}$, angle of attack, $\alpha = 5^\circ$, freestream velocity, $U = 60\, \text{m/s}$, liquid water content, LWC = $1.1\, \text{g/m}^3$ and temperature, $T = -8^\circ\, \text{C}$. In this case, the water impinges on the wing at the leading edge forms a film at the leading edge (Fig. 5(a)). The water film breaks into rivulets which advance down the wing (Figs. 5(b–d)). The downstream extent of the water film begins to freeze (Fig. 5(e)). Near the leading edge, the water film begins to exhibit roughness (Figs. 5(f)). As the roughness elements grow and the ice layer thickens, the extent of the liquid water film begins to retreat back towards the leading edge (Figs. 5(g–h)).
IV. Digitizing features in icing video

Extracting features from the raw video frames is not a straightforward process because there is no direct meaningful relationship between the pixel counts in the recorded image and the physical configuration of the water and ice; e.g., there is no direct relationship between the pixel count and the water depth, nor phase, etc. The images are maps of the light intensity scattered or reflected from the wing, water, and ice. Light diffusely scattered from the wing or ice appears as grayscale values. Pixels that are saturated come from places with surface normals that direct specular reflections toward the camera.

![Reference image](image1.png)

(a) Reference image

![Image frames](image2.png)

(b) $T = 6.53s$

(c) $T = 6.67s$

(d) $I_{ref} = I_{T=6.67} - I_{T=0}$

(e) $\Delta I = I_{T=6.67} - I_{T=6.53}$

**Figure 6:** As a measurement, the icing video shows the amount of light reflected from the wing, ice, and water surface from the flood illumination source. Extracting quantitative information requires image processing techniques to pick out features from the background.

We see the images in Figs. 3, 4, and 5 and our visual system performs image processing in combination with a priori knowledge to interpret the images as evolving ice shapes. Watching video of the icing process provides the visual system with much additional information over a random single snapshot given without context. By having information such as the initial image of the the wing without ice as a reference, or such as the sequence of images that provide a cue on how the image is changing, we can better interpret the intensity texture map as physical features. Here, we look apply a similar image processing scheme as our visual system, where we analyze the images in the context of the whole video sequence to identify features in the ice formations. Here, we use the total image change, $I_{ref}$, and the image time derivative, $\Delta I$, to extract information about the transient icing process. Figure 6 illustrates how these quantities are derived from the image data. The initial reference image of the wing without water or ice is shown in Fig. 6a, and two snapshots of the wing during the icing process separated by a short time interval are shown in Figs. 6b and 6c. Figures. 6d and 6e show the intensity difference maps from using the initial wing reference image (Eqn. (6)) and from using the previous time image as a reference (Eqn. (8)), respectively. Mathematically,
these images are expressed as
\[
I^i_{\text{ref}} = I^i - I^0, \quad \text{(6)}
\]
\[
\Delta I^i = I^i - I^{i-1}. \quad \text{(7)}
\]

A. Leading edge ice measurement

Differencing the images with the initial reference produces an intensity map where the pixel counts represent the amount that the image has changed from the initial state. Physically, the difference in intensity must be caused by the presence of water or ice (neglecting image noise). Whether the intensity difference is positive or negative is not physically meaningful; however, the absolute value of the change indicates the presence of water or ice. Figure 7 shows the leading edge ice growth as a function of time. The data was calculated by identifying the first location in front of the wing with meaningful change in the pixel count compared to the initial reference; namely, for every span position \( y \),
\[
x^i_{\text{LE}} = \text{first}(I^i_{\text{ref}}(x) > \epsilon). \quad \text{(8)}
\]

The resulting time series of leading edge profiles is further reduced to the average leading edge thickness and the root-mean-square fluctuation about the straight line fit through the extracted profile. Therefore, the measurement characterizes evolution of the leading edge ice thickness and the leading edge roughness.

B. Rivulet geometry measurement

Unlike the leading edge ice that develops over an unlit background, the rivulets form over the wing, which results in relatively low contrast total image differences \( I_{\text{ref}} \) because both the bare and rivulet-covered wing surfaces scatter light with similar intensity. However, as the rivulets advance along the wing, their convex geometry results in an optical lens effect which results in large differences between successive images as the rivulet advances. Here, a dark rivulet outline occurs because of the rivulet curvature, while bright regions occur at the center of the leading rivulet drop where light is collected, and specular reflections occur at the edge of the rivulet where the surface normal reflects the illumination toward the camera, producing saturated pixel regions. Differencing sequential images produces an intensity map where the pixel counts highlight the regions that are changing due to the presence of water and/or ice. Whether the image intensity differences are positive or negative is not important; however, a large absolute value of the change indicates significant changes in the water or ice. Because the rivulet geometry is traced out during the runback process, integrating the square of the image derivatives results in an intensity map that highlights the rivulets. Figure 8 outlines the process for digitizing the rivulets. First, the rivulet image is computed according to Eqn. (9) (Fig. 8a). Next, the image region containing the rivulets is identified and cropped (Fig. 8b). Thresholding allows the image to be partitioned into rivulet and non-rivulet regions, where non-rivulet pixels are zeroed. Finally, the rivulet image is summed along the chord direction, reducing the data to a rivulet image distribution across the span (Fig. 8c).
\[
a^i(x, y) = \Delta I^i(x, y) - \text{MedianFilter}(\Delta I^i(x, y)) \quad \text{(9)}
\]
\[
A(x, y) = \Sigma_i a^i(x, y)^2. \quad \text{(10)}
\]

C. Runback time series

To track the transient runback, we use the time sequence of the image time derivatives to locate the regions on the wing where water and ice activity causes fluctuations in the recorded images. We calculate the spanwise-averaged icing activity according to Eqn. (11); therefore, for each time and chordwise position, we have a
Figure 8: The time-accumulation of image differences is used to extract the rivulet geometry in the runback region. First, the square of sequential image differences are integrated in time according to Eqn. (9) (a). Then, the image region containing the rivulets is identified (b). Finally, the rivulet geometry is extracted from the chordwise sum of image intensity (c).

map describing how much the image was changing across the span due to icing (Fig.9). By digitizing the contour map of this image/icing activity $A$, we can extract the time evolution of various features during the icing process (e.g., the water film and rivulet runback). Figure 9 shows the digitized map of the icing activity, and compares a snapshot from the recorded video with the corresponding digitized features indicated. Icing feature time sequences were digitized by manually clicking the features in the activity map and assigning them labels according to the physical process they represent. The manually clicked points were interpolated using a shape-preserving cubic interpolant to provide a feature location estimate at all times throughout the duration of the icing event.

$$a'(x, y) = \Delta I'(x, y) - \text{MedianFilter}(\Delta I'(x, y))$$  \hspace{1cm} (11)

$$A'(x) = \sum_y a'(x, y)^2.$$  \hspace{1cm} (12)

First, the leading edge ice growth was digitized using this activity map method and compared to the previous measurement outlined in sec. A to provide a comparison and validation of this method for digitizing the runback features. The leading edge ice thickness is shown in Fig. 10 using coarse dashed lines. The good agreement between the two measurements is evidence that digitizing the activity map provides an accurate measure of the time-evolution of the transient icing features.

Five different icing features are digitized in Fig.9: the leading edge ice thickness, the location of the water film front during the initial runback, the location of the maximum rivulet runback, the location of the receding water film, and the location of maximum image activity (denoted “bulk liquid”). In the case of the leading edge ice thickness, the film runback, and the film recession, the features were identified as the first chordwise location where the image activity map deviated significantly from the background levels. Conversely, the rivulet runback feature was identified as the rearmost chordwise location image activity map deviated significantly from the background levels. The maximum image activity location was identified approximately along the ridge corresponding to the maximum image activity and represents the region where the water interacts with growing ice roughness features, leading to pooling and rapidly changing images due to ice growth and water surface waves.
Figure 9: Overview of the water and ice activity, A (top) and a close-up view of the activity during initial run back (bottom). The plots show log(A) to highlight low-level details. The bottom left shows a snapshot of the icing runback with the chordwise locations of the tracked features.
V. Results and Discussion

A. Leading edge ice

The top-down 2d-projected view provides a measurement of the ice accretion dimensions that lie within the measurement plane; thus, the measurement captures the thickness of the ice that forms on the leading edge, and it captures the lateral extents of the features on the wing. Measuring the dimensions in the chord-span binormal direction requires a different technique, such as the digital image projection.\(^\text{15}\)

Figure 10 shows the long-time growth of the leading edge ice for $U = 20$ and $40\,\text{m/s}$ trials. The accumulated ice is proportional to the accumulation parameter $a$ given in Eqn. (5). Here, the time derivative of the accumulation parameter relates to the rate of ice accumulation; namely,

$$\frac{da}{dT} = \frac{\text{LWC} \cdot U}{L}.$$ \hspace{1cm} (13)

The rate of accumulation is proportional to the freestream velocity, which is reflected in the measured leading edge ice thickness growth as the freestream velocity is approximately doubled from $U = 20\,\text{m/s}$ to $40\,\text{m/s}$ (Fig. 10). In less than 5 min, the leading edge ice growth exceeds 7 mm and 10 mm at $U = 20\,\text{m/s}$ and $40\,\text{m/s}$, respectively. Compared to the maximum wing thickness of 12.2 mm, this represents a significant change in the airfoil shape.

Additionally, the dotted lines in Fig. 10 indicate the $\pm 1$ standard deviation of the roughness variations about the mean location. We see that as the leading edge ice develops and grows, so does the roughness of the ice features at the leading edge. Previous work has shown that the stagnation point at the leading edge of an airfoil in glaze ice conditions is unstable and develops 3-dimensional disturbances at low Mach numbers.\(^\text{17}\) These disturbances grow and manifest themselves as ice roughness at the leading edge.

B. Rivulet geometry

The formation of rivulets during the initial runback is a process that plays an important role in the formation of ice downstream of the leading edge ice growth. As the ice at the leading edge grows, it acts as a barrier to the collection of water on the wing surfaces behind it, especially if the flow separates over the leading edge ice growth; however, the rivulets may still stick out into the separated flow where it can continue to collect water and continue to grow. This process is a positive feedback loop where ice features which protrude out the furthest grow the fastest.\(^\text{10}\) Additionally, the rivulets themselves can lead to detrimental aerodynamic performance by increasing turbulence, leading to decreased lift-to-drag ratios.\(^\text{18}\) The geometry of the rivulets is important to determining the aerodynamic effect, with larger rivulets resulting in decreased aerodynamic performance.

The measured rivulet geometry is shown in Fig. 12, with the processed image data on top highlighting the configuration of the rivulets on the wing, with the digitized rivulet locations shown below. The extracted rivulet geometries are summarized in Table 1. As illustrated in sec. III, the slowest wind speed case produced no rivulets. This is an important difference between icing conditions and conditions with water present, but without freezing temperatures. Pervious water runback measurements show that rivulet formation does occur at lower wind speeds\(^\text{15}\) in the absence of freezing conditions, and demonstrates that the rivulet width decreases with increasing wind speed. Here, the measured rivulet spacing and width decrease with increased freestream velocity. Furthermore, the rivulet width decreases faster than the rivulet spacing such that rivulet...
Figure 11: The digitized rivulet structure for $U = 40$ and $60 \text{ m/s}$ trials is shown. The top figures show the time-accumulated image changes used to extract the rivulet features. The bottom figures show the rivulet intensity profiles across the span with circles denoting the locations of digitally extracted rivulets.

Table 1: Extracted rivulet geometry. The number of rivulets, $N$, is given for the span field of view as pictured in Fig. 8. The spacing, $\delta$, is the mean center-to-center spacing between neighboring rivulets. The area fraction, $AF$, is the area covered by the rivulets versus the total area in the rivulet region; namely, the fraction of Fig. 8b with non-zero pixel data. The rivulet width, $w$, is the mean width across a single rivulet.

<table>
<thead>
<tr>
<th>Freestream, $U$ [m/s]</th>
<th>Number of rivulets, $N$ [-]</th>
<th>Spacing, $\delta$ [mm]</th>
<th>Area fraction, $AF$ [-]</th>
<th>Width, $w$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>14</td>
<td>$2.71 \pm 0.60$</td>
<td>0.50</td>
<td>1.35</td>
</tr>
<tr>
<td>60</td>
<td>17</td>
<td>$2.09 \pm 0.93$</td>
<td>0.29</td>
<td>0.65</td>
</tr>
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</table>
area fraction—the rivulet area divided by the total area covered by rivulets—decreases with increasing wind speed.

C. Icing runback

The ice accretion process on the wing begins with runback of the water film and its breakup into rivulets. This process transports water from the collection area to other regions of the wing, playing an important role in the final ice shape. The runback is driven by the aerodynamic shear stress. Figure 12 compares the measured film and rivulet runback for the three wind speeds tested. The film runback location measures the extent of the very thin water film. In contrast, the rivulets form as the aerodynamic shear stress drives a flow toward the contact line, where water accumulates and the water thickness increases. Eventually the advancing film front breaks into rivulets and runs back. In the case of \( U = 20 \text{ m/s} \) where no rivulets formed, the maximum film runback region is shown, which consists of the thicker water beading up at the contact line, which is similar to the water beads advancing at the head of the rivulets.

![Figure 12: A comparison of the time evolution of the film and rivulet runback for the different icing conditions measured. The black dashed line indicates the maximum runback speed of the \( U = 60 \text{ m/s} \) rivulet at \( u_{riv} = 53.8 \text{ mm/s} \).](image)

Table 2: Measured mean water film and rivulet runback speed. The mean speed is calculated from the data in Fig. 12 by dividing the total runback distance by the time until the maximum runback distance was reached. In cases such as the \( U = 40 \text{ m/s} \) rivulet runback, the instantaneous velocity may sometimes be much higher.

<table>
<thead>
<tr>
<th>Freestream, ( U ) [m/s]</th>
<th>Film runback, ( u_{film} ) [mm/s]</th>
<th>Rivulet runback, ( u_{riv} ) [mm/s]</th>
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</thead>
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<tr>
<td>20</td>
<td>1.23</td>
<td>2.38</td>
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<td>40</td>
<td>3.14</td>
<td>7.96</td>
</tr>
<tr>
<td>60</td>
<td>4.66</td>
<td>23.3</td>
</tr>
</tbody>
</table>

With increasing wind speed, high shear stress drives the film and rivulet flows. Figure 12 shows that the film and rivulets advance more quickly at higher speed. The fastest wind speed tested had rivulet runback speeds reaching \( u_{riv} = 53.8 \text{ mm/s} \). The mean film and rivulet runback speeds are summarized in Table 2. Surprisingly, the film advances further along the chord at higher wind speeds as well. This is in contrast to simple water runback experiments without freezing conditions\(^{15}\) where film extent decreased with increasing wind speed, instead forming rivulets further upstream. This difference between freezing and

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non-freezing conditions indicate that the heat transfer process that governs the rate of ice formation also plays an important role in the formation of the rivulets.

The stair-step shape of the rivulet runback extent in the \( U = 40 \text{ m/s} \) and \( 60 \text{ m/s} \) measurements (Fig. 12) demonstrates that the rivulet runback is not a continuous process. Here, the rivulet runs back for a short distance and then becomes pinned before running back again. The rivulet may freeze or simply become too diminished in volume to further advance the contact line. The runback continues when enough upstream water beads up and travels along the rivulet until it meets the rivulet head and continues the rivulet advancement. This process is illustrated in the bottom icing activity map in Fig. 9 along the green line denoting the rivulet runback feature. Initially, the rivulet runs back as traced out in the green line before stalling at the time around \( t = 10.0 \text{ sec} \). A second bead of water begins to propagate along the rivulet path starting around \( t = 10.5 \text{ sec} \) until it catches up to the end of the rivulet at \( t = 11.0 \text{ sec} \) where it advances the rivulet another \( 10 \text{ mm} \).

VI. Concluding Remarks

Here we have presented results of wind tunnel icing experiments on a NACA 0012 wing. High speed video shows the transient process involved in determining the ice shapes on the wing. We implemented image processing techniques to make quantitative measurements of key icing features involved in the transient icing processes. The tools developed here provide a method for investigating the transient icing physics, which have been largely been ignored in previous wind tunnel icing studies.

The measurements make use of the time-resolved image sequences of the icing process to extract features based on image differences from a reference image, as well as from sequential image differences. The long-term ice accretion at the leading edge was found to grow according to the accumulation rate of water. The agreement between the two different measurement techniques for extracting leading edge ice thickness validate the icing activity map method for extracting the time-evolution of transient icing features on the wing, allowing the water film and rivulet runback processes to be quantified.

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