An Experimental Investigation on the Dynamic Water Runback Process Over an Airfoil Surface Pertinent to Aircraft Icing Phenomena

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Aircraft icing is a serious threat to aviation safety. Icing accretion process usually interacts with surface water run back flow under glaze icing condition. Advancing the technology for safe and efficient aircraft operation in icing conditions requires a better understanding of the underlying physics of complicated thermal flow phenomena pertinent to aircraft icing phenomena, both for the icing itself as well as for the water runback along contaminated surfaces of wing surface. In the present study, an experimental investigation was conducted to characterize the surface wind-driven water film/rivulet flows over a NACA 0012 airfoil in order to elucidate the underlying physics of the transient surface water transport behavior pertinent to aircraft icing phenomena. The experimental study was conducted in an icing research wind tunnel available at Aerospace Engineering Department of Iowa State University, was developed and applied to achieve Quantitative measurements of the unsteady film/rivulet flows were achieved by a novel digital image projection (DIP) measurement system. The measurement results reveal clearly that, after impinged on the leading edge of the NACA0012 airfoil, the micro-sized water droplets would coalesce to form a thin water film in the region near the leading edge of the airfoil. The formation of rivulets was found to be a time-dependent process, which relies on the initial water runback flow structure. The time-averaged leading edge film thickness follows the Nelson’s $x^{1/4}$ scaling law for all of the free stream velocities.

Nomenclature

\begin{align*}
c & = \text{Chord length of airfoil} \\
C_d & = \text{Drag coefficient} \\
F_c/f_c & = \text{Resisting force induced by surface tension/unit width resisting force at film/rivulet front} \\
F_d/f_a & = \text{Aerodynamic drag/unit width aerodynamic drag at rivulet front} \\
F_i/f_l & = \text{Inertia force of rivulet flow/unit width inertia force of rivulet flow} \\
h & = \text{Film/rivulet thickness} \\
LWC & = \text{Liquid water content} \\
Q/q & = \text{liquid flow rate/unit width flow rate} \\
R & = \text{Diameter of water beads} \\
Re & = \text{Reynolds number} \\
u & = \text{Local instantaneous stream wise velocity} \\
U & = \text{local time-averaged stream wise velocity} \\
U_\infty & = \text{free stream velocity} \\
We & = \text{Weber number} \\
We_a & = \text{Aerodynamic drag to surface tension, } We_a = \frac{\rho_a U_\infty^2 \Delta H}{\sigma} \\
x & = \text{Coordinate along chord length direction} \\
\mu & = \text{Dynamic viscosity} \\
\rho & = \text{Density} \\
\sigma & = \text{Water surface tension} \\
\theta & = \text{Contact angle}
\end{align*}

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\[ \tau = \text{Shear stress} \]

Subscripts
\[ a = \text{Variables defined in air, notice } \theta_a \text{ means advance contact angle} \]
\[ r = \text{Variables defined in rivulet flow} \]
\[ w = \text{Variables defined in water} \]

I. Introduction

Aircraft icing is due to the supercooled water droplets impinging and subsequent icing in the surface of the airplane. There are two types of icing accretion processes: glaze icing and rime icing. In a dry regime, all the water collected in the impingement area freezes on impact to form rime ice. For a wet regime, only a fraction of the collected water freezes in the impingement area to form glaze ice and the remaining water runs back and can freeze outside the impingement area. Because of its wet nature, glaze ice is the most dangerous type of ice. It causes airplane performance degradation (Bragg et al. 1986) and inhibits the control of airplane (Ranaudo et al. 1991).

Water beads, rivulets and film flows run back along the airfoil surface during glaze icing condition (Olsen and Walker 1986). The behaviors of surface water run back flows will redistribute the impinging water mass and disturb the local flow filed, as a result, influence the icing accretion process and aerodynamic characteristics of the aircraft. In this work, an experimental investigation was conducted to quantify important micro-physical processes of water runback on an airfoil surface which are pertinent to aircraft icing.

Wind-driven thin water films over airfoil surfaces and flat plates have been studied both theoretically and experimentally. Early experimental investigations revealed that the water runback flow on an airfoil can be divided into fully wetted film flow range and partly wetted rivulets range (Gelder and Lewis 1951). Hansman and Turnock’s experiment showed that surface tension of a liquid significantly altered the glaze ice shape (Hansman and Turnock 1989). The similarity of surface water dynamics is essential to glaze icing scaled model test (Anderson 2004). Kind (2001) claimed that one more parameter, i.e., Weber number based on the thickness of liquid film, should be considered as a critical scaling parameter in the glaze icing tunnel test. Anderson and Feo (2002) suggested that the non-dimensional water film thickness itself might be a critical dimension that affects the ice accretion. Theoretical investigations are done to precisely predict the water film thickness. Nelson et al., (1995) showed that the water film thickness increases as flowing along a flat plate by a \( h \approx x^{1/4} \) scale law. Feo (2000) and Rothmayer (2003) presented a scaling law that relates steady film thickness with Reynolds number and Liquid Water Content. However, there are only a few film thickness measurements, and none of them directly measure film thickness on airfoil surface. The scaling laws related to leading edge film thickness have not yet been demonstrated experimentally.

The unsteady microphysical processes such as surface waves, transient water-air contact lines and moving of rivulet fronts influence the water transport behaviors during the aircraft icing process. The wave generation of wind-driven liquid films over flat plate had been examined for small disturbances (Craik 1966; Miesen and Boersma 1995, Ueno and Farzaneh 2011). Tsao et al. (1997) investigated the stability of a thin film over an airfoil surface. In those works, water-air interface becomes unstable and surface waves arise under certain film thickness conditions. Boundary layer theories were developed to describe the more complex interfacial waves on thin liquid films (Rothmayer and Tsao 2000; Rothmayer et al. 2002). The formation of local roughness and water beads were observed during airfoil icing tests (Olsen and Walker 1986; Anderson and Ruff 1998). The incipient motions of water beads and film flows over roughness had been examined by Rothmayer and his colleagues (Rothmayer and Tsao 2001; Wang and Rothmayer 2009; Rothmayer and Hu 2013). The mechanism of initial roughness formation underneath wet surfaces was considered as the instability effect of ice surface (Otta and Rothmayer 2009; Rothmayer and Hu 2012). A number of studies have been done to model the formation of rivulets (Al-Khalil et al. 1990; Thompson and Jang 1996; Thompson and Marrschello 1999; McAlister et al. 2005). However, experimental investigations on surface water flows over aerodynamic shapes generally illustrated the macro water flow phenomena by analyzing videos taken in the experiments (Hansman and Barsotti 1985; Olsen and Walker 1986; Hansman and Craig 1987; Thompson and Jang 1996). The important unsteady phenomena mentioned above are not well revealed in those studies.

In the present study, a digital image projection (DIP) system is used to achieve non-intrusive thickness measurements of wind-driven water droplet/rivulet flows over a NACA0012 airfoil. The DIP technique is based on the principle of structured light triangulation. The digital projector projects line patterns of known characteristics onto the test specimen (i.e., a water droplet/rivulet on a test plate for the present study). The pattern of the lines is modulated from the surface of the test object. By comparing the modulated pattern and a reference image, the 3D profile of the test object with respect to the reference plane (i.e., the thickness distribution of the water
droplet/rivulet flow) can be retrieved quantitatively and instantaneously. The fundamental principles and more details of the technique including image correlation algorithm, displacement to height calibration procedure, accuracy verification and sample measurements were described in Zhang et al. (2015). The DIP technique has been successfully applied in evaluating the transient behavior of wind-driven rivulets (Zhang and Hu 2016a). In current study, the transient distributions of film thicknesses over an airfoil surface are used to elucidate the mechanisms of the unsteady surface water transport phenomena such as onset motion of initial droplets, surface wave generation, and rivulet formation. The time-averaged film thickness distributions are used to validate the film thickness scaling laws.

In the following sections, section 2 describes the complete experiment set up for measurements of wind-driven thin water rivulet/film flows over a NACA 0012 airfoil surface. Section 3 reveals the transient process of developing water runback flow. Section 4 discusses the film thickness scaling law based on the average film thickness obtained in the experiment. Section 5 presents conclusion remarks.

II. Experiment set up

Figure 1 illustrates the schematic of the experiment setup for the thickness measurement of thin water rivulet/film flows over a NACA 0012 airfoil surface. The experiments were performed in ISU Icing Research Tunnel (IRT). The wind tunnel has a plexiglass test section with cross section dimension of 25.4x25.4cm (WxH). Three internal mix air atomization nozzles are installed in the upstream of the tunnel contract section. Pressure regulators were used to control the spray nozzle’s air and water supply incoming pressure. The spray water flow rate was monitored by a flow meter (Omega FLR1010ST-D). The liquid water content (LWC) and droplet mean volume diameter (MVD) can be controlled by adjusting the spray nozzle water pressure and air supply pressure. In order to avoid spray water beads blocking the light paths of camera and projector, only two of the spray nozzles were used to generate a cloud of spray water droplets. The spray air supply pressure and spray water supply pressure for the nozzle were 45 and 20 psi respectively. Because of the air pressure is much higher than the water pressure, the generated droplets had a small MVD (10–50μm). According to previous measurements and simulations of the impinging droplet collection efficiency (Papadakis and Liu 1994; Francois et al. 1999; Da Silveira et al. 2003), the direct impinging range was assumed to be less than 5% chord length. A small amount of flat white latex paint (1% volume fraction) was added into the spray water for enhancing the diffusive reflection on the liquid surface. Notice that, the penetration depth for the 1% latex suspension is 0.6mm. The penetration depth is in the same order of the leading edge film thickness. The penetration depth error can be compensated for using a lookup table method. The details of the correction can refer to (Zhang and Hu 2016b). A NACA0012 airfoil model with chord length c=101mm was installed in the center of the test section. The model was 3D printed by a rapid prototyping machine. To improve the diffuse reflectivity of the model surface, the test model was coated with flat white paint. The painted surface of the test model was carefully sanded. In present study, all experiments were conducted with zero angle of attack (α = 0°) at room temperature T∞ = 20°C). The velocity of the oncoming airflow in the test section was adjusted from U∞ = 10m/s to U∞ = 30m/s. Consequently, the corresponding Reynolds numbers based on the chord length of the airfoil and the airflow velocity varied from Re = 0.67 × 10^5 to Re = 2.02 × 10^5.

The DIP system set up is generally the same as our previous experiments (Zhang et al 2013). Dell DLP projector (M109S) was used to project cross line grid to the upper surface of the airfoil model. A CCD camera (DMKBU2104) with a Pentax C1614-M lens (F/1.4, f=16mm) were used for image acquisition. The CCD camera and the projector were synchronized by a digital delay generator. Camera speed was set to 30FPS with an exposure time of 2ms. For each measurement, 1200 images (60S) were recorded after the spray nozzle was active. The field of view of the CCD camera is approximately 11cm×8cm. The projected grid size on the captured image is 7x7 pixels (1.1x1.1mm), which is also the interrogation window size for the cross-correlation calculation. The relative location of camera and projector was aligned along the span wise direction to suppress the mirror reflection of the film/rivulet surface and avoid fake cross-line displacement due to the curvature surface of the model. Figure 2 shows the typical reference and deformed displacement images. The pictures of the projected cross grid pattern on the airfoil model surface were used as reference images, as shown in Fig. 2(a). Compared with a flat plate substrate, the grid crosses were pre-bended. Figure 2(b) shows the typical displacement vector field due to presence of film/rivulet flows. Those vectors were converted to actual film/rivulet thickness using the displacement-to-height parameter map that was obtained in the calibration process.
III. Transient water runback behaviors and discussion

Figure 3 and Figure 4 shows the time history results of thickness measurements of thin film and rivulet flows under wind speed from $U_\infty=10\text{m/s}$ and $U_\infty=20\text{m/s}$. Seen from Fig. 3 and Fig. 4, DIP measurement system successfully characterized the whole process of water surface flows. The global structure of rivulet flows were well reconstructed, especially the irregular saw tooth like shape. Rivulets’ fronts, rivulets’ width, interfacial waves on the rivulets surface were clearly indicated. The results demonstrate the robustness and feasibility of DIP measurement system. The uniform film flow thickness near the leading edge region was well detected as well.

Figure 3 and Figure 4 illuminate the water runback flow procedure under different free stream velocities. As displayed in Fig. 3, under low wind speed condition (i.e., $U_\infty=10\text{m/s}$), several tiny rivulets were generated near the airfoil leading edge right after the spray water was on (Fig. 3(a)). Then the impinging droplets wetted the direct impinging range and formed a uniform water film. At the same time, those tiny rivulets merged with each other as they flowed downstream. Next, a uniform film flow front with a hump shape was detected (Fig. 3(b)). As the film flowed further downstream, surface waves appeared and the film front became unsteady and displayed saw tooth shape. At a certain point the film fronts edge broke into rivulets (Fig. 3(c)). After the rivulets flowed back to the tail of the airfoil, the wetted area of the airfoil became stable and did not change any more (Fig. 3(d)). For higher wind speed cases (i.e., $U_\infty=20\text{m/s}$), tiny rivulets appeared and merged with each other at the initial spray stage (Fig. 4(a), and Fig. 4(b)). Meanwhile, the spray water tended to flow into the generated rivulets. Then the rivulets grow larger and flowed downstream. No hump shape film front was observed. Finally, the runback flow exhibited uniform film flow at the front of the airfoil surface and rivulets flowed beyond the film flow range (Fig. 4(d)). The water runback flow behavior under free stream velocity $U_\infty=15\text{m/s}$ was in between the runback behaviors of $U_\infty=10\text{m/s}$ and $U_\infty=20\text{m/s}$. The runback flow behaviors was very similar to the cases of wind speed $U_\infty>20\text{m/s}$. The flow phenomena of $U_\infty=25\text{m/s}$ and $U_\infty=30\text{m/s}$ could be represented by the flow phenomena of $U_\infty=20\text{m/s}$.
Figure 3 DIP measurement results of wind speed $U_\infty = 10\text{m/s}$.

Figure 4 DIP measurement results of wind speed $U_\infty = 20\text{m/s}$. 

(a). $t = t_0 + 0.5s$
(b). $t = t_0 + 1.0s$
(c). $t = t_0 + 2.0s$
(d). $t = t_0 + 6.0s$
Based on the flow features described above, we divide the unsteady water runback behavior into three stages: stage I-the initial stage, stage II-the “stagnation” stage, and stage III-the rivulet formation stage (Fig. 5a-5e). Figure 5f shows the time history of the maximum rivulet thickness location of the first left rivulet in Fig. 5a-5e. Note that the maximum rivulet thickness will be at the rivulet front besides sometime at surface waves peaks, Thus, Fig. 5f represents the transient location of rivulet front. After performing a force balance analysis, the three-stage transient water transport behaviors were found to be the consequence of the force balance between the aerodynamic drag (shape drag), the rivulet inertia force, and the capillary resisting force. The schematic of the flow structures and the force balance analysis are plotted in Fig. 6. At the initial stage, tiny rivulets appeared near the airfoil leading edge. Then the generated rivulets slowly flowed downstream (Fig. 5a). This phenomenon is consistent with Olsen and Walker’s observations of the experiment cases above freezing temperature conditions (Olsen and Walker 1986). The impinging water will first form water beads in the direct impinging range. The forces act on the generated water bead can be expressed as:

\[ F_c = F_d + F_r \]  

In equation (1), \( F_d \) is the aerodynamic shape drag, \( F_r \) is the skin friction, and \( F_c \) is the capillary resist. As the diameter of the impinging droplets were very small (10-50\( \mu \)m), the direct impinging range was near the stagnation line of the airfoil (the stage I shown in Fig. 6). According to the Blasius solution, the skin friction coefficient approaches infinity at this range. The skin friction is considered as very large and is the dominant force. Therefore, no much aerodynamic shape drag is required to move the water bead. The diameter of the water bead will be small when it starts to move. As a result, tiny rivulets are generated in the initial stage.

Figure 5b-5d show the runback behaviors of the stagnation stage. The tiny rivulets slowed down or stagnated at a certain location (around 15% chord length). Meanwhile, the impinging water continuously flowed into the rivulets. The tiny rivulets merged with each other and grew larger and larger. The stagnation of wind driven rivulets over airfoil is similar to the stagnation behavior of rivulets over flat surface. In our previous investigation, the rivulet stagnation behavior on a flat surface was revealed by a force balance criterion (Zhang and Hu 2016a). The rivulet stagnation happened when the aerodynamic drag plus the inertia force exceeds the resisting of surface tension:

\[ \sigma(1-\cos \theta_a) = \frac{\rho \cdot \tau_a^2 \cdot h_{rb}}{6 \mu_w^2} + \frac{1}{2} \rho_s U_\infty^2 (h_{rf} - h_{rb})C_d \]  

\[ f_c = \sigma(1-\cos \theta_a) \]  

\[ f_i = \frac{\rho \cdot \tau_a^2 \cdot h_{rb}^3}{6 \mu_w^2} \]  

\[ f_d = \frac{1}{2} \rho_s U_\infty^2 (h_{rf} - h_{rb})C_d \]  

In equation (2)-(5), \( \sigma \) is the surface tension, \( \theta_a \) is the advance contact angle, \( \tau_a \) is the shear stress at the water-air interface, \( h_{rb} \) is the rivulet body thickness, \( h_{rf} \) is the rivulet front thickness, \( C_d \) is the drag coefficient. Similar to the Zhang and Hu’s (2016a) research, the rivulet width was much larger than the rivulet thickness. Therefore, in equation (2), the 2D force balance criterion is used. In the initial stage, the skin friction drives the rivulet moving forward. The shear stress \( \tau_a \) can be estimated by the Blasius solution along a flat plate, which gives \( \tau_a \sim Re_s^{-1/2} \). From equation (4), the rivulet inertia force \( f_i \) is decreased linearly with the wrap distance \( f_i \sim s^{-1} \). The inertia force \( f_i \) at the stagnation range is much smaller than the inertia force near the airfoil leading edge. On the other side, the capillary resisting force \( f_c \) is depends on the advance contact angle and the surface tension of liquid. It means the capillary resisting force is not changed with the wrap distance and the free stream velocity. A moving rivulet front requires the same amount of aerodynamic drag increment to compensate the reduction of inertia force. From equation (5), a much thicker rivulet front is needed to generate enough aerodynamic drag. Consequently, the tiny rivulets stagnated and grew larger. Notice that \( f_d \sim U_\infty^2 \), a thicker rivulet front thickness is required under low free stream velocity. The experimental results conform to the force balance analysis. Under free stream velocity \( U_\infty = 10m/s \), the rivulet front thickness was about \( h_{rb} = 0.6mm \) (Fig. 3b), and the rivulet front thickness increased with wrap distance (Fig. 3c). Meanwhile, the rivulet front thickness was only about \( h_{rb} = 0.25mm \) under free stream velocity \( U_\infty = 20m/s \) (Fig. 4b). Because of the impinging water flowrate was fixed, it took more time to generate a thicker rivulet front. Therefore, the duration of the “stagnation stage” was longer under a low free stream velocity (i.e., \( U_\infty = 10m/s \) and \( U_\infty = 15m/s \) in this study). The thicker rivulets also merged with each other and generated
film front (Fig. 3b). The finding of “stagnation” stage may cause the initial roughness formation in icing environment. The slow moving or stagnation behavior of rivulets provide enough water mass and enough icing time. There is a higher probability for local ice buildup. Otta and Rothmayer confirmed that an increase of local ice height result in more cooling from the airflow and cause rapid ice accretion at that point (Otta and Rothmayer 2009). Thus, a tiny ice protruding could be the start point of icing instability and grow to an ice roughness.

The rivulet formation stage under a relative higher free stream velocity condition is shown in Fig. 5e. High raised rivulet fronts were already generated in the stagnation stage. The aerodynamic drag at the high raised rivulet front was large enough to overcome the capillary resisting. The rivulet kept moving forward to the tail of the airfoil. The Surface waves were observed on rivulet surfaces. Our previous investigation proved that the surface wave will not significantly influence the wind-driven rivulet flow for a long time scale. The overall rivulet motion will still be a “dynamic” uniform motion (Zhang and Hu 2016a). This fact is further corroborated in current study. Seen from Fig. 5f, a quasi-uniform rivulet motion is detected during the rivulet formation stage. Notice that, the surface waves did not appear at the rivulet formation stage. It confirms with the wind-induced waves theories (Craik 1966; Miesen and Boersma 1995). According to the observation and stability analysis, the unstable film surface occurs when film thickness reaches a critical thickness. For the current study, the thickness of film/rivulet increased along the chord length. Surfaces waves appeared after the thickness of film/rivulet reached the critically thickness.

The film break up to rivulets process was observed under low free stream velocity conditions (Fig. 3b, 3c). This type of rivulet formation is essentially caused by the instability of the film front contact line. A local contact line protruding leads to more water flow from the film flow, which causes a higher local film thickness. The thicker film front causes an aerodynamic drag increment, which makes the film front move faster than the surrounding contact line. Thus, the curvature of the local contact line becomes larger and larger and finally develops to a rivulet. As the film flow rate, free stream velocity increases, this contact line instability effect increases. Thus, the surface wave speeds up the rivulet formation process by a sudden increasing of flow rate. The uniform film front can not form for high free stream velocity.

Due to the limitation of the measurement technique, previous rivulet formation models did not consider the unsteady rivulet formation procedure. Thompson and Jang (1996) and Thompson and Marrochello (1999) introduced a rivulet formation model which stated that the rivulets will be formed where the air shear stress surpasses the capillary resisting force. According to Thompson’s paper, rivulet formation occurs at the location where

\[ 0.5C_{f,e} \rho U^2 \cos \theta = \sigma(1 - \cos \theta) \]

This is the aerodynamic skin-friction coefficient, \( \sigma \) is the liquid surface tension, \( \theta \) is the liquid-solid contact angle. A surface-tension skin-friction coefficient was defined from equation (6):

\[ C_{f,e} = \frac{2\sigma}{\rho U^2 \cos \theta} (1 - \cos \theta) \] (7)

The rivulet forms when the local skin friction coefficient surpass the surface-tension skin-friction coefficient. There is an apparent error in Thompson’s model. The unit of the left side of equation (6) is \( N/m^2 \), while the unit of the right side is \( N/m \). Actually, as we discussed above, the skin friction only play an important role near the leading edge of the airfoil. At the rivulet formation range, aerodynamic drag is much more important than the skin friction. Equation (7) should be modified as \( C_d \left[ 2\sigma(1 - \cos \theta) \right]/\left[ \rho U^2 \cos \theta (h_{rf} - h_{Rb}) \right] \) if inertia force of the rivulet is neglected. Even if equation (7) is corrected, the force balance model is not an effective analysis method for rivulet formation. Force balance model is based on the assumption that the rivulet forms from the film breaks up. As discussed in the above paragraphs, the rivulet formation on the airfoil surface was an unsteady process. For higher wind speed conditions, the rivulet formed shortly after the stagnation stage. The final film flow range was not yet generated at that time. For low wind speed \( U_{\infty} = 10 m/s \), before the hump shape film front broke into rivulets, the hump film front was moving from \( x/c = 0.15 \) to \( x/c = 0.5 \). The aerodynamic drag definitely surpassed the capillary resisting force during the period. As we stated, the formation of rivulet was caused by the instability of the water-solid contact line. Force balance criterion is only a necessary condition for rivulet formation but not the sufficient condition.

The other popular rivulet formation model is the minimum total energy (MTE) model. Al-Khalil presented a rivulet model base on three criterions: mass flow rate of film and rivulet is equal, energy of film flow and rivulet is equal, and Boersma (1995).
equal, rivulet energy is minimum at the steady rivulets configuration (Al-Khalil et al. 1990). The three criterions are modeled by the following equations in Al-Khalil’s paper:

\[ Q_f = Q_r \]  \hspace{0.5cm} (8)

\[ E_f = E_r \]  \hspace{0.5cm} (9)

\[ \frac{\partial}{\partial F} \left[ E_r \frac{\lambda}{F} \right] = 0 \]  \hspace{0.5cm} (10)

Where F is the wetness factor and \( \lambda \) is the ratio of rivulet width to wetness factor. Wetness factor F is defined as the fraction of the surface that is wetted by runback flow at a particular downstream location. By applying those three criterions, Khalil introduced a critical dimensionless film thickness \( h^+ = h_o^2 / [6 \mu_o \sigma / \rho_w \tau^2] \), where \( h_o \) is dimensional local film thickness, \( \tau \) is shear stress, and \( h^+ \) is the minimum dimensionless thickness of an unbroken, stable film. Al-Khalis’s model considers the film thickness near the leading edge of an airfoil is thinner than the critical film thickness. Within the impinging limit, spray water force to wet the whole surface of airfoil. Rivulet immediately forms right behind the impinging limit. However, for low free stream velocity, the hump film front is the thickest area of the whole film and the film flow region definitely exceeds the impinging limit (Fig. 3b, 3c). For higher wind speed, the formation of rivulets during the “stagnation” stage influenced the final rivulet configuration. The formation of rivulets is a highly unsteady process. The minimum energy state of an assumed steady state film-rivulets configuration is not applicable for the unsteady water runback flow over airfoil surface.

![Figure 5](image_url)

(a) Stage I, \( t = t_0 + 0.3s \)  \hspace{0.5cm} (b) Stage II, \( t = t_0 + 0.5s \)  \hspace{0.5cm} (c) Stage II, \( t = t_0 + 0.8s \)

(d) Stage II, \( t = t_0 + 1.1s \)  \hspace{0.5cm} (e) Stage III, \( t = t_0 + 1.5s \)  \hspace{0.5cm} (f) Stable stage, \( t = t_0 + 6.0s \)

Figure 5 Transient water runback behavior. (a) stage I: initial stage. (b)-(d) stage II: “stagnation” stage. (e) stage III: rivulet formation stage (f) Time history of maximum rivulet thickness locations. The first rivulet from left in figure (a)-(e) is plotted here.
Figure 6 Sketch of transient water runback behavior. Static water beads were generated in the initial stage. Aerodynamic skin friction was the dominant force, which pushed the water bead moving forward and left. Tiny rivulet formed in the initial stage. Skin friction decreased along chord length and led to a decrease of the rivulet flow inertia force. Thus, rivulets stagnated or slowed down at the stagnation stage. High raised rivulet front led to an aerodynamic shape drag, which driven the rivulet flow downstream during the rivulet formation stage.

IV. Transient water runback behaviors and discussion

Time average rivulet/film thickness distributions are shown in Fig. 7. The time-averaged thickness was calculated by 500 measurements after the steady wetted area was formed. It is displayed clearly that, the film/rivulet thickness, leading edge film length, the spacing between rivulets and rivulets’ width all decreased with increasing of free stream velocity. The leading edge film lengths changed from 40% chord to 25% chord as the free stream velocity changed from 10m/s to 30m/s. To elucidate the tendency of surface water distribution along chordwise direction, average surface water thicknesses at the centerline of rivulets are plotted in the right column of Fig. 7. Rivulets near the center of measurement windows are selected to extract the data. Shown in Fig. 7, the surface water thickness kept increasing along the chord length of the airfoil for all the free stream velocities. The leading edge film thickness changed from 0.05 to 0.4 mm. From wind speed 10m/s to 25m/s, The average rivulets' width at streamwise location x=60mm (60%c) were 18.5mm, 11.2mm, 5.6mm, 3.3mm respectively. It is interesting that the wetted factor (F=50%) was almost the same for wind speed 15m/s, 20m/s and 25m/s. Due to the limitation of measurement spatial resolution (1.1×1.1mm), the average rivulets’ width under the condition \( U_{\infty} = 30 \text{ m/s} \) is not accurate, we establish the width was around 2mm.

(a). Average film thickness
(b). Film/rivulet thickness profile

(a). Wind speed \( U_{\infty}=10\text{m/s} \)
(a). Average film thickness

(b). Film/rivulet thickness profile

(c). Wind speed $U_\infty=20\text{m/s}$

(d). Wind speed $U_\infty=25\text{m/s}$
Nelson presented a non-similar boundary layer theory for water film flow in flat plate driven by laminar airflow (Nelson et al. 1995). Nelson assumed the velocity profile within the water film is linear. Using two boundary conditions: (i) Flow rate of film is constant, (ii) Shear stress at the water-air interface is continuous, Nelson derived that film thickness is proportional to $x^{1/4}$, where $x$ denotes the distance away from the flat plate leading edge. Tsao et al., (1997) and Ueno and Farzaneh (2011) obtained the same scaling law using similar but slightly different derivation. In Ueno & Farzaneh’s paper (2011), wind-driven thin water film flow over a flat plate was modeled. Water was supplied at the leading edge of flat plate with a constant flow rate. Ueno made the following approximations: (i). airflow and water flow are both laminar flows. (ii). The velocity profile within the water film is linear, in the other word, (i.e., film flow is dominated by viscous effect and the inertia force can be neglected). (iii). The obtained film thickness is steady state value. The influence of the presence of surface waves is ignored. (iv). The only water supply in Farzaneh’s simulation was at the leading edge of flat plate, no spray droplet impinging was considered.

Then, Blasius’s equation was used to model the undisturbed laminar air flow. For water film, Ueno assumed the following scaling: $h_0 = C_1 x^a$, $u_a = C_2 x^b$. Where $u_a$ denotes the water-air interface horizontal velocity. The constants, $C_1$, $C_2$, $a$ and $b$, were determined from the two boundary conditions. First, the volumetric water flow rate per width is constant:

$$Q/\delta = \int_0^h u_a dy = C_1 C_2 x^{a+1} \int_0^1 u_a dy,$$

(11)

Where $Q/\delta$ is the unit width film flow rate, $u_\ast$, $y_\ast$ is normalized interfacial velocity and thickness. Second, the horizontal shear stress at interface is continuous:

$$\frac{C_1}{C_2} \mu_a \frac{du_a}{dy} \bigg|_{x_\ast} x^{b-a} = \left( \frac{U_\infty}{2\nu_0} \right)^{1/2} \mu_a \frac{d^2 f_a}{dy^2} \bigg|_{y_\ast=0} x^{-1/2},$$

(12)

Where $\mu_1, \mu_a$ is the viscosity of water and air, $f_a$ is the normalized stream function, $f_a''$ is a constant. From equation (12), $b - a = -1/2$. $Q/\delta$ is constant along streamwise direction, form Equation (11), $a + b = 0$. Consequently, $a = -1/4$, $b = -3/4$. $C_1$, $C_2$ are also determined by equation (11), (12). The relationship between film thickness and film flow rate, wind speed, distance away from leading edge is expressed as:

$$h_b \sim \left( \frac{Q/\delta}{U_\infty} \right)^{1/2} U_\infty^{-3/4} x^{3/4},$$

(13)

For the current work, the spray water flow rate $Q_s$ was fixed. Suppose that the LWC distribution is uniform within the whole test section, then the LWC is proportional to $Q_s/\delta_\infty$, unit width film flow rate $Q/\delta_\infty$ should be proportional to $Q_s$. Thus, the unit width film flow rate is the same for all of the free stream velocities. Figure 8 plots
the film thickness versus the $\frac{1}{4}$ power of wrap distance $s$ within film flow range. Wrap distance $s$ is defined as the arc length that starts from the stagnation point. Seen from Fig. 8, the leading edge film thickness was 0.05-0.4mm. The Couette flow approximation within the film is reasonable. The film thickness profiles are generally linear curve when the wrap distance $s^{1/4}$ > 1.9 ($s$ > 13mm, $x$ > 11.5%). The results are encouraging and show a very good agreement with Nelson’s theory (The $x^{1/4}$ scaling is first introduced by Nelson). The thickness profile near the airfoil leading edge is not proportional to $x^{1/4}$ due to two reasons: (i) Nelson’s theory assumes a laminar boundary layer. The boundary layer needs to be developed at a certain distance away from the leading edge. The power law of $h \sim x^{1/4}$ will start from a certain point downstream. (ii) The leading edge of the NACA 0012 airfoil is a curvature shape. Flat plate boundary layer solution can be directly applied to curve shape when the local curvature is small. However, the curvature of airfoil leading edge is relative large, where the flat plate boundary layer solution may not valid in the area.
V. Conclusions

An experimental study was conducted to achieve water film/rivulets flow thickness measurements on a NACA0012 airfoil surface at five different wind speeds by using a digital image projection (DIP) system. The whole process of surface water film/rivulet flow was well revealed from the time-resolved film/rivulet thickness distribution measurements. The formation of rivulets highly relies on the initial flow structure. Film thickness scaling law is evaluated by the time-average film thickness profile. The conclusion derived from the experiments can be summarized as follows:

- The transient water runback process can be divided into three stages: initial stage, “Stagnation” stage and rivulet formation stage. Tiny rivulets generated in the initial stage. Those tiny rivulets would stagnate or slow down at a certain down stream location. During the stagnation stage, the slow downed rivulet front became larger, and merged with each other. Film front was observed under low free stream conditions. The film front then broke into rivulet, and flowed to the tail of the airfoil. For higher free stream velocity, the high raise rivulet front kept moving downstream to the tail of airfoil.

- The transient water runback behaviors can be explained by a force balance analysis. During initial stage, static water beads formed near the airfoil leading edge. The aerodynamic skin friction is very big near the stagnation point. It drove the water beads flow downstream and generated many tiny rivulets. The aerodynamic skin friction decreases along the chord length. The inertia force of rivulet decreases along chord length correspondingly. Meanwhile, the capillary resisting force depends on the advanced contact angle and can be considered as constant along chord length. Thus, the aerodynamic drag compensates the loss of inertia force. The rivulets front became thicker to generate enough aerodynamic drag. The rivulet formation procedure is found to be the result of the instability of water-solid contact line.

- Time-averaged surface water thickness distributions were determined after the water transport paths became stable. The measurement results illustrate that, the chordwise length of the water film near the airfoil leading edge, the spanwise spacing between the water rivulets and the width of each rivulet were all found to decrease monotonically with the increasing oncoming wind speed.

- The propagation part of the leading edge uniform film thickness is proportional to $s^{1/4}$.

Figure 8 Film thickness vs $s^{1/4}$ power scaling
Acknowledgments

The research work was partially supported by National Aeronautical and Space Administration (NASA) – Grant number NNX12AC21A with Mr. Mark Potapczuk as the technical officer. The support of National Science Foundation (NSF) under award number of CBET-1064196 with Dr. Sumanta Acharya as the program manager is also gratefully acknowledged.

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American Institute of Aeronautics and Astronautics


