An Experimental Investigation on Wind-Driven Rivulet/Film Flows over a NACA0012 Airfoil by Using Digital Image Projection Technique

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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. 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. A novel digital image projection (DIP) measurement system was developed and applied to achieve quantitative measurements of the thickness distributions of the surface water film/rivulet flow at different test conditions. 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. Water rivulets were found to be generated as the water film flow runs backs. The width and the spacing of the water rivulets were found to decrease monotonically with the increasing wind speed.

I. Introduction

Aircraft icing occurs when a cloud of supercooled droplets impinging and freeze onto the airplane surface during flight (Gent et al, 2000). In glaze icing conditions, water beads, rivulet and film flows run back along the airfoil surface (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. Rothmayer reported a series of theoretical studies on fully interaction of water-air-ice field under icing conditions with surface waves and ice roughness field presents (Rothmayer et al., 2002, Wang and Rothmayer, 2009, Otta and Rothmayer 2009, Rothmayer and Hu, 2013). He reported the trapping effect of water film flow through roughness field, stability analysis on water interfacial waves and ice accretion process near stagnation line region. Those investigations enhance the theoretical understanding of the physics of water transport behavior on aircraft icing process. However, experimental investigations about surface water flows over aerodynamic shapes generally illustrate the macro water flow phenomena by analyzing videos taken in the experiments (Hansman and Barsotti. 1985, Olsen and Walker. 1986, Hansman and Anthony. 1987, Thompson and Jang, 1996). The important micro-physical processes such as film thickness distribution, contact line moving velocity and wet surface area can not be well revealed in those experiments. Advanced experimental techniques capable of providing accurate measurements to reveal the micro-transient phenomenon of surface water behavior like film thickness, wavy surface structure, rivulet width, contact angle and rivulet front speed are highly desired.

In the present study, a digital image projection (DIP) system is developed to achieve non-intrusive thickness measurements of wind-driven water droplet/rivulet flows over a NACA0012 airfoil in order to elucidate the mechanisms of the unsteady surface water transport process pertinent to icing and rain phenomena. The DIP technique is based on the principle of structured light triangulation in a similar manner as a stereo vision system but replacing one of the cameras for stereo imaging with a digital projector. 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

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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 about wind-driven film flow over flat plate were described in our previous paper (Zhang et al., 2013).

In the following sections, section 2 describes the complete experiment set up for measurements of wind-driven thin water rivulet/film flows over NACA 0012 airfoil surface. Section 3 shows water film/rivulet thickness measurement results. Section 4 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 NACA 0012 airfoil surface. The experiments were performed in ISU-Goodrich Icing Research Tunnel (IGIRT). The wind tunnel has a plexiglass test section with cross section dimension of 25.4×25.4cm (W×H). Three internal mix air atomization nozzles are installed in the upstream of the tunnel contract section. Pressure regulators were used to control the incoming pressure of spray nozzle’s air and water supply. 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 pressure of spray water and air supply. 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 cloud of spray water droplets. The spray air supply pressure and spray water supply pressure for the nozzle are 45 and 20psi respectively. A small amount of flat white latex paint was added into spray water for enhancing the diffusive reflection on the liquid surface. A NACA0012 airfoil model with chord length 101mm was installed in the center of the tunnel test section. The model was 3D printed by rapid prototyping machine. To improve the diffuse reflectivity of the model surface, the test model was coated with flat white paint. The white painted surface of the test model was carefully sanded. In present study, all experiments were conducted with zero angle of attack at room temperature. Four different wind speeds 10m/s, 15m/s, 20m/s and 25m/s (Re=0.67×10^5 -1.69×10^5) were employed.

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 grid cross line to 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 is set to 30FPS with 2ms exposure time. For each measurement, 1200 images (60s) were recorded after the spray nozzle was active. The field of view of CCD camera is approximately 11cm×8cm. The projected grid size on the captured image is 7×7 pixels, which is also the interrogation window size for cross correlation calculation. The relative location of camera and projector was aligned along the span wise direction to suppress the mirror reflection of 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 projected cross grid pattern on the airfoil model surface were used as reference images. (Fig. 2(a)). Compare with flat plate substrate, the grid crosses were pre-bended. Figure 2(b) shows the typical displacement vector field due to present of film/rivulet flows. Those vectors were converted to actual film/rivulet thickness.
Figure 1. Experiment set up for spray water rivulet/film flow test

Figure 2. Typical experimental DIP images.

(a). Reference image.  
(b). deformed image with water rivulets

III. Results and discussion

Figure 3-6 shows the time history results of thickness measurement of thin film and rivulet flows under wind speed from 10m/s to 25m/s. Seen from Fig3 and Fig4, 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 were clearly indicated. The results experiments demonstrate the robustness and feasibility of DIP measurement system. The uniform film flow thickness near the leading edge region is well detected as well. However, near the leading edge film thickness is the same level of the typical background measurement error (0.1 pixel displacement in the raw picture or 20 micrometer), the accuracy of the measurement need to be verified. Note that these measurements were conducted with camera field of view cover the whole airfoil. Better measurement accuracy might be achieved by refined level of measurement windows that focus on the nose region of the airfoil.

As displayed in the figures, for low wind speed case, the spray water first generates uniform film flow near the leading edge of airfoil. Then the film flow front becomes thicker as it transports downstream along the airfoil upper surface. As the film flow further flow downstream, surface waves appear and the film front become unsteady and display saw tooth shape. At certain point the film fronts edge break into several rivulets. After that the boundary of the rivulets are stable and do not change any more. High wind speed case will also evaluate to stable wetted area flow which is similar to low speed flow. However, the rivulet formation mechanism is different with low speed case. Following paragraph will illustrate this interesting topic. The phenomenon of present study is similar to the observation of “gel-coated” airfoil surface water flow reported by Hansman and Barsotti (1985).
Figure 3. DIP measurement results of wind speed 10m/s.

Figure 4. DIP measurement results of wind speed 15m/s.
Figure 5. DIP measurement results of wind speed 20m/s.

a). T=2.0s  
b). T=4.0s  
c). T=6.0s  
d). T=8.0s

Figure 6. DIP measurement results of wind speed 25m/s.

a). T=1.0s  
b). T=2.0s  
c). T=3.0s  
d). T=4.0s

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Figure 7 shows the film front break point at wind speed 10m/s and 15m/s. The left column of Fig. 7 shows the film/rivulet thickness distribution at the break point of the film flow. The right column of figure 7 displays the film thickness profile at the breaking point along streamwise direction. Fig. 7 revealed that rivulet formation is highly influenced by water surface waves under low wind speed condition. The film front breaking is always happened near the highest wave crest region with a wave tough area behind it. The wave crest thickness is approach 0.9 mm which is 15% of maximum airfoil thickness. As a result the air pressure force on the backside of the water wave is considerable strong. It surpasses the surface tension restraining force and causes the rivulet front flow downstream. This rivulet formation mechanism is different with Thompson’s rivulet formation model which only considered the balance of air shear stress and water surface tension restraining force (Thompson and Jang, 1996, Tompson and Marrochello, 1999). For higher wind speed test, film and rivulet flow is developed simultaneously. No distinct film front was observed during the rivulet formation process (Fig. 8). At the initial stage of water impinging, the amount of water is not enough to generate uniform film. Due to the nonuniform droplet distribution and disturbance of airflow, rivulet fronts formed and flow downstream. After the initial stage, impinging water tends to flow through rivulet path to minimize surface tension force. As shown in Fig. 8, the leading edge film thickness is very thin which indicates very small changes of air pressure. The finally stable rivulet and film division line can be considered as a balance of air shear stress and surface tension restrain.
Time average rivulet/film thickness distributions are shown in Fig.9. The time average thickness is calculated by 500 measurements after the steady wetted area formed. It is displayed clearly that, as wind speed increase, film/rivulet thickness, leading edge film range length, the spacing between rivulets and rivulets’ width are all decrease. The leading edge film ranges are changing from 40% chord length to 20% corresponding to wind velocity changing from 10m/s to 25m/s. To elucidate the tendency of surface distribution along chord wise direction, average surface water thicknesses at the centerline of rivulets are plotted in figure 10. Rivulets near the center of measurement windows are selected to extract the data and the data extraction lines are parallel with chord length. The surface water thickness keep increasing along the chord length of the airfoil for wind velocity 10m/s, 15m/s and 20m/s. A sharp increasing of water thickness were detected near the trailing edge. The thickness profiles trend conforms with Cai’s calculation film thickness profile on S809 wind turbine airfoil (Cai et al., 2012). As can be seen in Fig10(a), a thickness slope turning point is located in the maximum airfoil thickness location (30% of chord length). In front of 30% chord length, the spray droplets impinging causes increasing film thickness even the wind speed accelerates in this area. Film/rivulet thicker effect is induced by the combination influence of slow down air speed and larger surface tension at the trailing edge of airfoil. Because of the imperfect thin rivulet boundary and the limitation of measurement spatial resolution, the data extraction line can not stay in the center of the selected rivulet. As a result, the thickness profile of case wind velocity 25m/s is different with other cases. The leading edge thickness is changing form 0.15mm to 20 micros as the wind speed increase. The other time, our system has a measurement uncertainty of 20 micros. For the wind speed 20m/s and 25m/s leading edge thickness profile may provide certain types of reference leading edge film thickness based on the film thickness changing slope is smooth.
Figure 9. Time average liquid film/rivulet thickness result

Figure 10. Time average film/rivulet thickness profile at the centerline of rivulets along chord wise direction
IV. Conclusions

An experimental study was conducted to achieve water film/rivulets flow thickness measurements on a NACA0012 airfoil surface at four 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 shape thickness sitribution measurements. Water-air interfacial waves were found to play an important role in determining the formation of the rivulets during the surface water run back. The conclusion derived from the experiments can be summarized as follows:

- At the initial stage of the impingment of the water droplets, surface water tends to generate a uniform film near the nose of airfoil. While the water film was found to grow thicker, and the front of the water film was found to become unsteady as the water file flow runs back. Finally, the film fronts would break to form water rivulets. After the rivulets begin to shred from the trailing edge of the airfoil, the wetted area on the airfoil was found to be almost stable and does not change any more.

- For the case with relatively low wind speed at $U_\infty = 10\text{m/s}$ and $15\text{m/s}$, the rivulet formation was found to be closely related to the behavior of the surface waves at the water-air interface. The film front was found to break near the region with the highest wave crest. The wave crest thickness was found to reach up to $0.9\text{mm}$. As a result, the air pressure on the backside of the water surface wave would become considerable large and performs as the primary force to induce the formation of the water rivulets.

- For the cases with relatively high wind speed (i.e., $U_\infty \geq 20 \text{m/s}$), the formation of the water film and rivulet flows was found to evolve simultaneously. Water rivulets were found to appear at the very initial stage of the impingment of water droplets. The oncoming surface water flows tend to be transported only through formed rivulet paths.

- Time-averaged surface water thickness distributions were determined after the water transport paths become 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 be decrease montonically with the increasing oncoming wind speed.

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