Surface Wetting Effects on a Laminar Flow Airfoil in Simulated Heavy Rain

R. John Hansman Jr.* and Martitia F. Barsotti†
Massachusetts Institute of Technology, Cambridge, Massachusetts

Wind tunnel experiments have been conducted on a natural laminar flow airfoil in a simulated heavy rain of 440 mm/h at a Reynolds number of 310,000 to assess the effect of surface wettability on the performance degradation due to rain. A significant loss of performance was observed for each of the three surfaces tested with the nonwettable, waxed surface being the most degraded (~75% reduction in maximum *L/D*) and the incompletely wettable epoxy gel coat being the least (~45% reduction). Accompanying the *L/D* loss was an effective reduction in angle of attack of up to 2 deg resulting from a downward translation of the C_L polar. In photographic observations, the runback water layer was found to bead on the wax surface and sheet on the wettable surfaces. The strong dependence on surface wettability of both the airfoil performance and the water behavior indicates that the degradation due to heavy rain is primarily a result of the roughening of the airfoil surface by the runback water layer. The observed performance loss could only be partially emulated by causing premature transition from a laminar to a turbulent boundary layer.

Nomenclature

C_L	= lift coefficient, based on chord
C_D	= drag coefficient, based on chord
D	= drop or bead diameter
h	= height of water layer
L/D	= lift-to-drag ratio
U	= flow velocity
We	= Weber number
α	= angle of attack
θ	= contact angle
ρ	= air density
σ	= surface tension

Introduction

THE aerodynamic penalty associated with flight through heavy rain recently has been postulated to be a contributing cause in several severe weather accidents.[1] In addition, the performance loss due to rain has a direct effect on achieved fuel efficiency. The aerodynamic problems associated with flight through rain are expected to become more important in the future with the increasing use of high-efficiency laminar flow airfoils which are characteristically sensitive to leading-edge contamination. In wind tunnel experiments, Dunham et al.[2] observed reductions of up to 20% in the maximum lift coefficient for a transport-type airfoil under simulated heavy rain conditions. The loss of lift was accompanied by an increase in drag and a reduction of up to 8 deg in the stall angle of attack. The primary mechanism for performance degradation due to rain is thought to be an effective roughening of the airfoil surface resulting from irregularities in the runback water layer.[1,3] Distributed roughness on the upper surface of an airfoil has been shown to have an effect on lift and drag[4-7]; however, details of how the water layer roughens the surface have not been fully investigated. Other effects of rain on aircraft performance, such as the momentum transfer from the drops to the vehicle and the increase in aircraft weight due to the water layer, have been estimated theoretically and are considered to be of secondary importance at rainfall rates less than 500 mm/h.[1,3,8] An additional effect of unknown magnitude is the splash behavior of the impinging rain droplets, which results in an ejecta fog of small water droplets just forward of the airfoil.[9,10]

Because the roughening effect of the runback water layer is considered a crucial factor in determining the performance degradation due to rain, it is important to understand how the water behaves on the airfoil. One aspect of the water film, which has not been fully investigated, is the effect of surface wettability. On a wettable surface the water is expected to sheet over the leading edge of the airfoil, resulting in a fairly smooth surface. On a nonwettable surface the water is expected to bead, causing an increase in roughness and a corresponding decrease in performance. This wettability effect has been observed qualitatively on the laminar flow airfoils of high-perfomance sailplanes. In sailplane competition the standard practice is to maintain a wettable surface on the airfoil due to the potential for perfomance loss under rain conditions.

In order to document the effects of surface wettability, wind tunnel experiments have been conducted on a natural laminar flow airfoil with various surface coatings in simulated heavy rain. The dry airfoil performance was compared with the wet performance of two incompletely wettable surfaces and a nonwettable surface. In photographic observations the behavior of the water layer was found to be markedly different for the three surfaces, with the nonwettable surface having the greatest degree of irregularity. All surfaces suffered a significant performance loss in wet conditions, with the nonwettable surface being the most degraded. The degradation could be partially emulated by intentionally tripping the boundary layer at various points. The results indicate that, for the experimental conditions observed, the water causes a premature transition from a laminar to a turbulent boundary layer and an effective reduction in airfoil camber. The work also provides some insight into the influence of surface chemistry on the behavior of water on the airfoil surface and how that behavior couples into the external aerodynamics.

Surface Wettability

The wettability of a surface with respect to a liquid commonly is defined in terms of the contact angle. The contact

Received Nov. 25, 1984; presented as Paper 85-0260 at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, Jan. 14-17, 1985; revision received July 25, 1985.

*Assistant Professor, Aeronautics and Astronautics. Member AIAA.
†Student Member AIAA.

angle θ is the characteristic angle at which a liquid rests on a surface (measured in the liquid). The relationship between contact angle and wettability is illustrated in Fig. 1, which shows the behavior of a liquid resting on wettable, nonwettable, and incompletely wettable surfaces. For a completely wettable surface the contact angle is 0 deg and the liquid tends to spread out evenly over the surface. The converse is true for a nonwettable surface on which the liquid tends to resist spreading. A completely nonwettable surface would have a contact angle of 180 deg, however, in practice, surfaces with contact angles of 90 deg or greater are considered nonwettable. Incompletely wettable surfaces are those with contact angles between 0 and 90 deg. On these surfaces the liquid will tend to spread in order to maintain its contact angle at the outer edge. For a given volume of liquid the scale height of the water will increase with contact angle and decrease with wettability.

Surface wettability considerations lead to the expectation that, on a fairly wettable airfoil, the water should tend to spread out in a thin layer over the surface and the primary roughening effect should be an increase in drag and decrease in lift due to waviness of the water film.[1] For nonwettable surfaces, the water should coagulate into discrete beads corresponding to the "large" roughness elements of Brumby,[4] who found a significant reduction in the lift coefficient at all angles of attack.

Experimental Setup

A schematic view of the experimental setup is shown in Fig. 2. A 16.2-cm (6-in.) chord Wortmann FX-67-K-170 natural laminar flow airfoil was mounted horizontally in a normal flight attitude on a two-component strain-gage balance in a 929 cm^2 (1 × 1 ft) low-speed tunnel. The airfoil test section was constructed of clear plexiglass to allow photographic observations of water on the airfoil. Rain was simulated by injecting water droplets (0.1-3.0 mm in diameter) from commercial rain simulation nozzles located in the top of the tunnel 1.5 m upstream of the airfoil model. The tunnel velocity was measured just upstream of the injection point and the nozzles were aimed so as to distribute the droplets as uniformly as possible in the test section. The nozzles were usually run with tap water, however, for some photographic studies a fluorescein dye was added to the water to enhance visibility. The liquid water content in the tunnel at the nominal operating Reynolds number of 310,000 (70 mph, 113 km/h) was inferred from nozzle flow rates to be 14.6 g/m^3 corresponding, in liquid water content, to an approximate rainfall rate of 440 mm/h.

The airfoil was tested with three different surfaces. The baseline surface was a clean epoxy gel coat that had been carefully sanded with 660 grit paper prior to testing. The air/water contact angle of this surface, θ, was measured to be 53 deg by observing a water drop on the surface through an optical comparator. A nonwettable surface (θ measured to be 90 deg) was obtained by applying a wax coating to the airfoil. There was some uncertainty in the testing of the soap-coated airfoil. This was due to experimental difficulties in applying the soap uniformly, causing physical and chemical irregularities on the airfoil surface.

Lift and drag measurements were made under dry and simulated rain conditions for each surface at 2-deg angle-of-attack increments from −1 deg through stall (angle of attack referenced to the zero-lift angle of attack in dry conditions). Two different types of photographic observations were made. In order to observe the behavior of the water layer on the upper surface, photographs were taken looking down through the plexiglass test section for each surface as a function of angle of attack. In addition, high-speed stroboscopic shadowgraphs were taken of the leading edge of the airfoil in order to observe droplet impact behavior.

Experimental Results

Lift and Drag Force Data

The effect of rain on airfoil performance can be seen in Fig. 3, where the lift-to-drag polar is plotted under simulated rain conditions for each surface tested as well as for a typical dry case. The Reynolds number for each run was 310,000 and the equivalent rainfall rate for the wet measurements was 440 mm/h. It can be seen that there was a significant loss of performance for all surfaces under wet conditions, consisting primarily of a downward translation and flattening of the L/D polar. The translation of the polar resulted in an effective decrease in angle of attack of up to 2 deg for the waxed case. This can be seen in the L/D and C_L curves of Figs. 3 and 4.

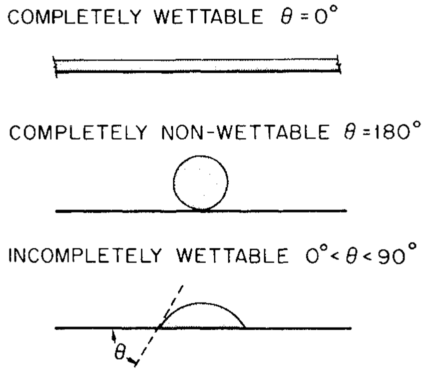

Fig. 1 Fluid behavior on surfaces of varying wettability.

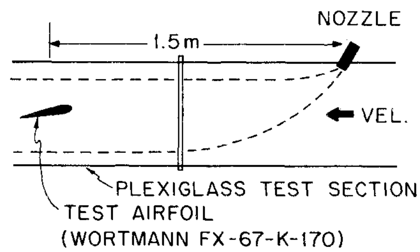

Fig. 2 Schematic view of setup for simulated rain experiments.

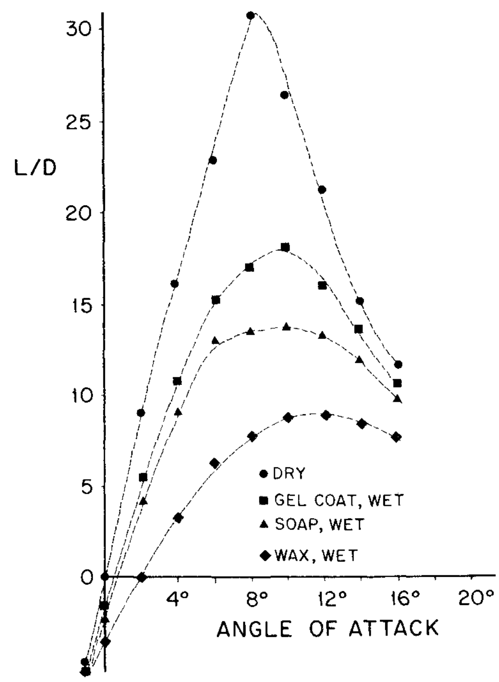

Fig. 3 Lift-to-drag ratio vs angle of attack for surfaces tested.

The waxed case is seen to have a zero intercept at 2 deg. Since the angle of attack is referenced to the zero-lift dry value, there is an effective reduction of 2 deg for the waxed case. There was a measurable difference between the various surfaces: the nonwettable, wax surface experienced the greatest performance degradation (~75% reduction in maximum L/D), and the smooth gel-coated surface experienced the least (~45% reduction).

One unexpected result was that the soap-coated surface, which should have had, by wettability considerations, the least degradation due to its low contact angle, actually experienced an intermediate performance loss. This is thought to have been caused by experimental difficulties in providing a uniform soap coating which produced physical and chemical irregularities in the airfoil surface. These irregularities are believed to have increased roughness in the water layer. This was confirmed by photographic observations where the water film was visibly rougher over the soap surface than over the gel coat.

The effect of rain can be seen in more detail in Figs. 4 and 5 where the lift and drag coefficients are plotted separately for the cases studied. In the C_L data the general downward translation under wet conditions observed in the L/D data is seen along with a slight reduction in the slope of the C_L curve. The angle of attack at maximum C_L is observed to increase under wet conditions. Because the zero C_L angle also increases, the angle-of-attack range between zero and maximum lift is approximately constant, however, there is clearly a loss of lift capability under wet conditions. Because of experimental limitations, it was not possible to exceed 16 deg angle of attack. For this reason, the maximum C_L angle of attack for the wet, waxed case that appears to exceed 16 deg could not be documented.

The gel coated and soaped surfaces have almost identical lift curves under wet conditions, with the waxed surface being significantly lower. In the drag data, both surface-roughening and momentum-transfer effects can be seen. There is a general increase in drag for all surfaces due to the transfer of momentum from the droplets to the airfoil. The magnitude of this increase is approximately 0.01, which agrees well with a value of 0.008 calculated for the wind tunnel conditions (N.B.: the effect of momentum transfer is amplified in these measurements due to the small scale of the model). A surface-dependent effect is also observable in the drag data, particularly at higher angles of attack. The wax surface is observed to have the highest drag, followed by the soap- and gel-coated surfaces. The drag curves are similar in appearance to the empirical curves derived by Dietenberger[7] for the effect of upper-surface roughness on an NACA 65A215.

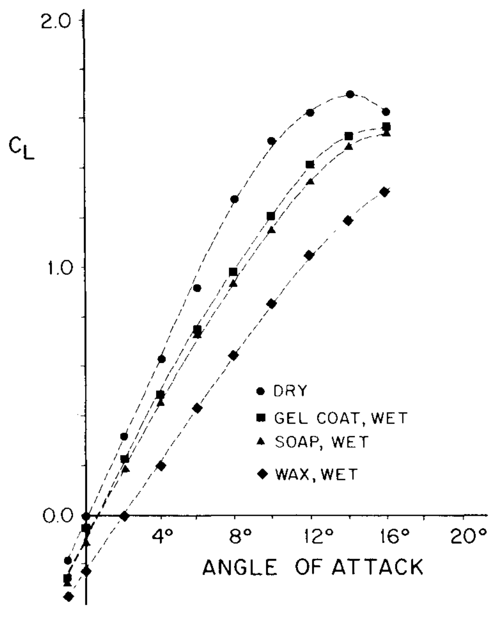

Fig. 4 Lift coefficient vs angle of attack for surfaces tested.

Photographic Results

In photographic observations of the upper surface of the test airfoil under wet conditions, three regions of distinctly different water behavior were observed. These regions are shown schematically in Fig. 6. From the leading edge of the airfoil extending back a short distance was the droplet impingement zone where the surface behavior was dominated by the droplet splashing. The splash craters discussed by Haines and Luers[1] are limited to this region. An example of a droplet

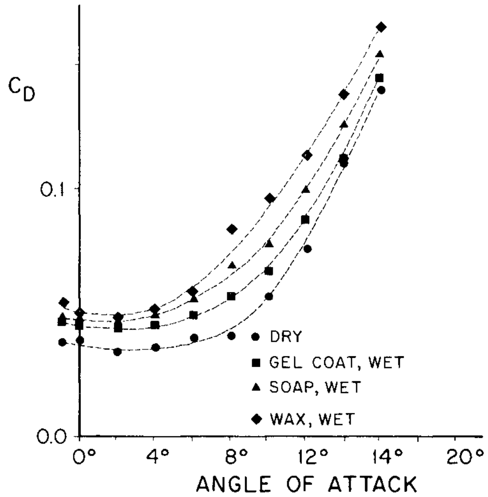

Fig. 5 Drag coefficient vs angle of attack for surfaces tested.

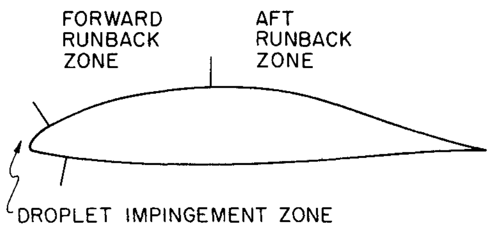

Fig. 6 Schematic view of regions where different water behavior was observed.

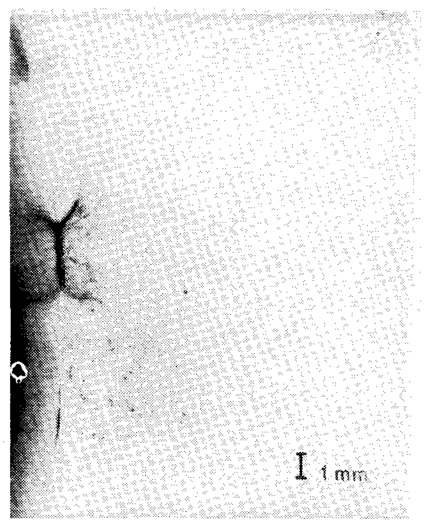

Fig. 7 Shadowgraph of airfoil leading edge showing a typical impact crater and the residual droplets that form the ejecta fog.

impact crater is shown in the high-speed shadowgraph (Fig. 7) taken looking down the airfoil leading edge at about the stagnation point. Also visible in the photograph are a few large impinging droplets ($D > 0.1$ mm) and a cloud of smaller droplets ($D \sim 40$ μm) extending approximately 1 cm from the surface which are the remnants of earlier impact craters. This cloud of small droplets is the bow wave ejecta fog observed previously by Hastings and Weinstein[9] and considered theoretically by Bilanin.[10]

In addition to the impingement zone, two distinct runback regions were observed. In the forward runback zone, located just aft of the impingement region, the water behavior is dominated by shear due to the external flow forcing any water on the surface downstream. In the aft runback zone, the external shear is reduced. The water tends to stagnate somewhat and factors such as surface tension become important. It may be possible to characterize these regions in terms of the Weber number *We*, which is the ratio of dynamic pressure forces to surface tension forces.

$$We = \rho U^2 h / \sigma$$

The forward runback region would tend to have a high Weber number where the aft region would have a lower value. The boundary between the forward and aft transition zones was normally located between the 20 and 50% chord position and observed to move forward with increasing angle of attack or decreasing freestream velocity.

The behavior of water in the runback zones can be seen in Fig. 8, where photographs of the airfoil upper surface are shown for each coating at an angle of attack of 8 deg. In the gel-coated case the water behaved in a manner very similar to the observations of Hastings and Weinstein.[9] The water spread out in a continuous film in the forward runback zone resulting in a fairly smooth surface. In the aft zone, as surface tension became more dominant, the water formed rivulets, or runoff streams, running directly to the trailing edge where a small amount of water collected until it was torn away by the external flow. The soap-coated airfoil had generally similar water behavior with two exceptions. The surface of the continuous film in the forward zone was noticeably roughened by irregular surface waves. The choppy surface of the water film appears as a specular reflection in Fig. 8. In addition, the runoff streams in the soap-coated case were broader and less regular than for the gel-coated surface.

The water on the wax-coated airfoil exhibited very different behavior. The high contact angle of the wax surface caused the water to bead in both the forward and aft regions. In the forward region the water formed small ($D \sim 1$ mm) beads elongated in the chordwise direction as they were dragged aft. This behavior is significantly different from the continuous film observed for the other cases. In the aft region the beads moved slowly downstream and coalesced with other beads until they were dragged to the trailing edge and torn away by the external flow. Beads as large as 9 mm across were observed in the aft region.

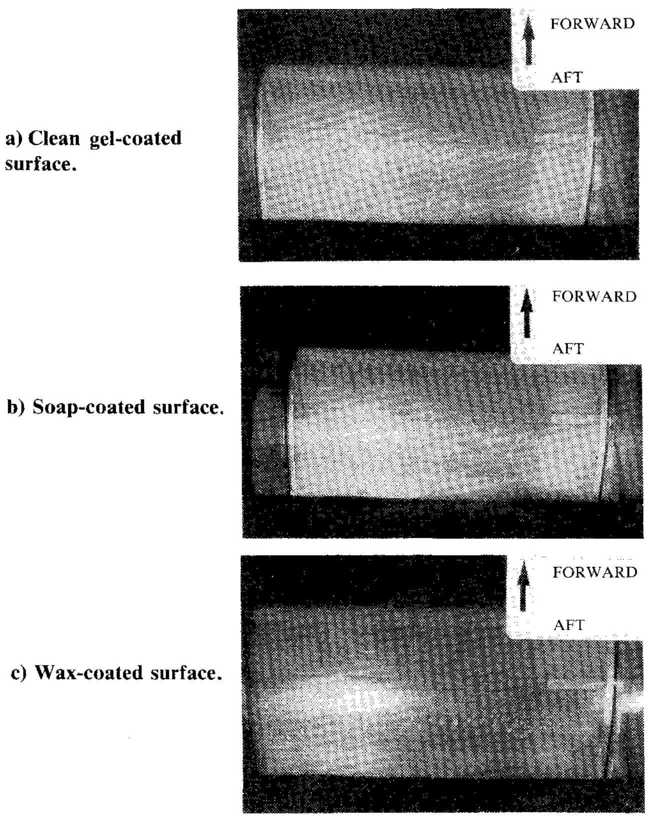

Fig. 8 Runback water behavior on the upper airfoil surface.

Boundary-Layer Tripping Results

In order to assess the extent to which the observed performance degradation may have been due to premature transition from a laminar to a turbulent boundary layer, under wet conditions, force measurements were made on the test airfoil with the boundary layer intentionally tripped at various positions.

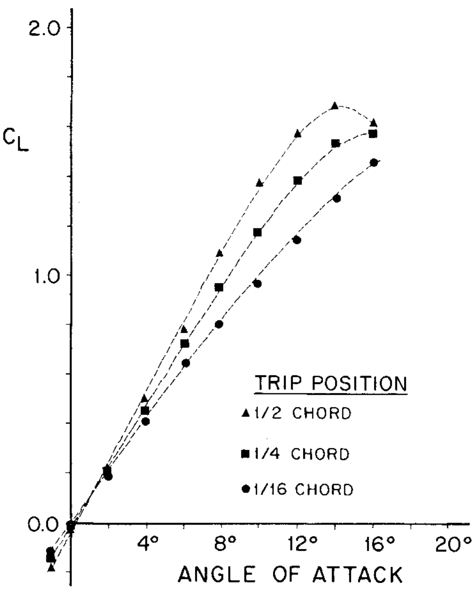

Fig. 9 Lift coefficient vs angle of attack with boundary layer artificially tripped.

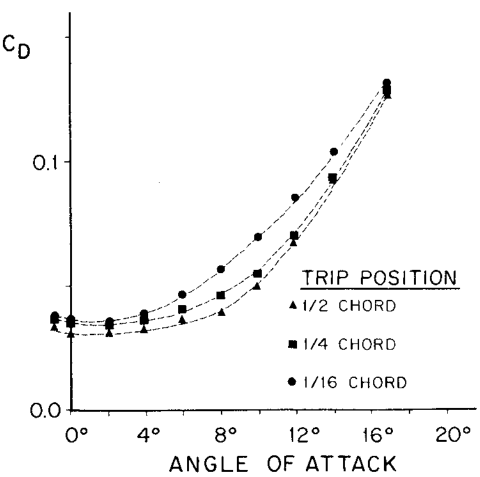

Fig. 10 Drag coefficient vs angle of attack with boundary layer artificially tripped.

The boundary layer was tripped at the 1/2-, 1/4-, and 1/16-chord positions by applying a thin (2-mm) strip of sand grains of approximately 0.3 mm average size. The results of these tests are shown as the C_L and C_D curves in Figs. 9 and 10. In Fig. 9 it can be seen that the slope of the C_L curve decreases as the boundary-layer transition point moves forward. This correlates with the reduction in slope observed under wet conditions. The downward translation of the C_L curve, which resulted in a decrease in the effective angle of attack along with the loss in lift under wet conditions, could not be emulated by tripping the boundary layer. The cause of this effect is, as yet, unidentified, but appears to be the result of the water reducing the effective camber of the airfoil by some mechanism.

In Fig. 10 the drag curve tends to increase as the transition point moves forward. The change in drag coefficient as the transition point moves from the 1/2 to 1/16 chord position is similar to the observed difference between the gel coat and the wax surface under wet conditions. Indeed, if the increase in drag coefficient due to momentum transfer from droplet impact is considered, then the remaining drag increase appears to be due to forward movement of the transition point caused by the water layer. The transition point appears to be near the leading edge for the wax surface, moving further aft for the soaped- and gel-coated surfaces, respectively.

Conclusions

Experiments have been conducted to determine the extent to which performance degradation of an airfoil in heavy rain is due to the effective roughening of the surface by the water layer. In addition, the effect of surface wettability was observed. For a natural laminar flow airfoil at a Reynolds number of 310,000 and a simulated rainfall rate of 440 mm/h, a significant reduction in performance was observed for each of the three surfaces tested. However, there was a large difference in the magnitude of the degradation for the different surfaces with the wax surface being the most degraded ($\sim$75% reduction in maximum L/D) and the clean gel coat being the least degraded ($\sim$45% reduction).

The large surface-wettability effect implies that the performance degradation is primarily a result of the roughening effect of the water that depends on the wettability of the airfoil surface. The fact that the minimum degradation was observed for a smooth wettable surface indicates that it may be possible to minimize the effects of heavy rain. This could be done either by providing wettable airfoil surfaces or by using surfactants (in a manner similar to the way glycol is used for icing) to increase the wettability of the water layer.

Further insight into the mechanism for performance degradation by rain was obtained in the photographic studies of the behavior of the water layer for the various surfaces. The wax surface, which suffered the greatest degradation, was characterized by beading of the water in both the forward and aft runback zones. On the other hand, the gel coat was characterized by a smooth water film in the forward runback zone and rivulets in the aft zone. Consequently, the waxed airfoil had a rougher surface due to the beading in the forward part of the airfoil. The roughness appears to have contributed to its greater performance loss. In addition to the runback behavior, droplet impact craters were observed near the leading edge of the airfoil, along with a cloud of small residual drops extending forward from the leading edge. Photographic observations were not conducted on the lower airfoil surface. In light of the apparent reduction in effective camber of the airfoil under wet conditions, a detailed comparison of the water behavior between the upper and lower surfaces would be advisable in the future.

One possible mechanism for performance degradation due to the water on the airfoil surface is a permature transition of the boundary layer from laminar to turbulent. In order to test this hypothesis the boundary layer was intentionally tripped at several positions. From a comparison of the lift and drag coefficients several conclusions could be drawn. The drag increase due to rain could be accounted for by an increase resulting from the premature transition of the boundary layer (further forward for the rougher water surfaces) and momentum transfer from the droplets to the airfoil. Only a small component of the decrease in lift could be attributed to movement of the transition point. The primary effect of the rain on the lift is a downward translation of the lift curve which results in lower lift and a reduction in the effective angle of attack both in flight and at stall. The rain appears to reduce effectively the camber of the airfoil. The mechanism for this reduction is unclear but is a surface-dependent effect. Further investigation is necessary to fully understand this effect.

Acknowledgments

This work was supported, in part, by the National Aeronautics and Space Administration, through the Langley Research Center, under Grant NAG-1-568.

References

[1]Haines, P. and Luers, J., "Aerodynamic Penalties of Heavy Rain on Landing Airplanes," *Journal of Aircraft*, Vol. 20, 1983, pp. 111-119.

[2]Dunham, R. E., Bezos, G. M., Gentry, C. L., and Melson, E., "Two-Dimensional Wind Tunnel Tests of a Transport-Type Airfoil in a Water Spray," AIAA Paper 85-0258, 1985.

[3]Rhode, R. V., "Some Effects of Rainfall on Flight of Airplanes and on Instrument Indications," NACA Rept. 803, 1941.

[4]Brumby, R. E., "Wing Surface Roughness Cause and Effect," *D.C. Flight Approach,* Vol. 2, 1978.

[5]Ljungstroem, B.L.G., "Wind Tunnel Investigation of Hoar Frost on a 2-Dimensional Wing Section With and Without High Lift Devices," Aeronautical Research Institute of Sweden, Rept. AU-902, 1972.

[6]Abbott, I. A. and VonDoenhoff, E., *Theory of Wing Section,* 2nd Ed., Dover Publications, New York, 1959.

[7]Dietenberger, M. A., "A Model for Nocturnal Frost Formation on a Wing Section," NASA CR-3733, 1983.

[8]Calarese W. and Hankey, W. L., "Numerical Analysis of Rain Effects on an Airfoil," AIAA Paper 84-0539, 1984.

[9]Hastings, E. C., and Weinstein, L. M., "Preliminary Indications of Water Film Distribution and Thickness on an Airfoil in a Water Spray," NASA TM-85796, 1984.

[10]Bilanin, A. J., "Scaling Laws for Testing of High Lift Airfoils Under Heavy Rainfall," AIAA Paper 85-0275, 1985.