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Repeatability of Ice Shapes in the NASA Lewis Icing Research Tunnel

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Tests were conducted in the Icing Research Tunnel (IRT) at the NASA Lewis Research Center to document the current capability of the IRT, focused mainly on the repeatability of the ice shape over a range of icing conditions. Measurements of drag increase due to the ice accretion were also made to document the repeatability of drag. The repeatability of the ice shape was very good at low temperatures, but only fair at near freezing temperatures. In general, drag data shows good repeatability.

Nomenclature

C_d = drag coefficient
c = airfoil chord length, in.
T_t = total air temperature, °F
t = ice accretion time, min
V_∞ = airspeed, mph
x = distance along the surface, in.
y = distance normal to the surface, in.
z = tunnel height measured from the floor, in.

Introduction

OVER the past few years, the Icing Research Tunnel (IRT) at the NASA Lewis Research Center (LeRC) has gone through several rehabilitations that have improved its capabilities in simulating real icing conditions. Some of the improvements include a new and more powerful fan motor, a new spray bar system, a new digital control system, and various improvements to the IRT structure. As a result, the IRT can now provide more accurate control of the airspeed and temperature, more uniform clouds covering a larger cross section of the test section, and lower liquid water content.

Although various test programs have been conducted in the IRT with the improved capabilities, there has not been a comprehensive test program to document the repeatability of the data obtained in the IRT. With the increasing use of experimental data for code validation work, there is a need for a repeatability study of the experimental ice shape and drag.

Tests were conducted to address the repeatability issue in the IRT during the months of June and July of 1991. The test matrix was focused to document the repeatability of the ice shape over a range of icing conditions including airspeed, air temperature, liquid water content (LWC), and spray time. During the tests, the drag increase due to the ice accretion and the surface temperature were also measured. In this article, results from the tests are presented.

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Description of the Experiment

Icing Research Tunnel

The NASA Lewis Icing Research Tunnel is a closed-loop refrigerated wind tunnel. Its test section is 6 ft high, 9 ft wide, and 20 ft long. A 5000-hp fan provides airspeeds up to 300 mph in the test section. The 21,000-ton-capacity refrigeration system can control the total temperature from −40 to 30°F. The spray nozzles provide droplet sizes from approximately 10- to 40-μm median volume droplet diameters (MVD) with LWC ranging from 0.2 to 3.0 g/m³. A detailed description of the IRT can be found in Ref. 1.

Test Model

The test model was a 6-ft-span, 21-in.-chord NACA 0012 airfoil with a fiberglass skin. The model was mounted vertically in the center of the test section. During all icing runs, the model was set at 4-deg of angle of attack.

Test Conditions

Test points were selected to study the effects of air temperature, LWC, and spray time on the repeatability of the ice shape. Test conditions are listed in Tables 1 and 2.

Table 1 lists the test points used to study the effect of air temperature on the repeatability of the ice shape. Temperatures were selected to cover glaze, rime, and transition re-

Table 1 Test conditions for the effects of air temperature and accretion time

Airspeed, mph	LWC, g/m³	Total temperature, °F	Ice accretion time, min
150	1.0	28, 25, 22, 18, 12, 1, −15	6
230	0.55	28, 25, 22, 18, 12, 1, −15	7
150	1.0	28, 25, 22, 18, 12	12

Angle of attack = 4 deg; MVD = 20 μm.

Table 2 Test conditions for the effects of LWC

Airspeed, mph	LWC, g/m³	Total temperature, °F	Ice accretion time, min
230	1.0	22	6
230	1.3	22	6
230	1.6	22	6
230	1.8	22	6

Angle of attack = 4 deg; MVD = 30 μm.

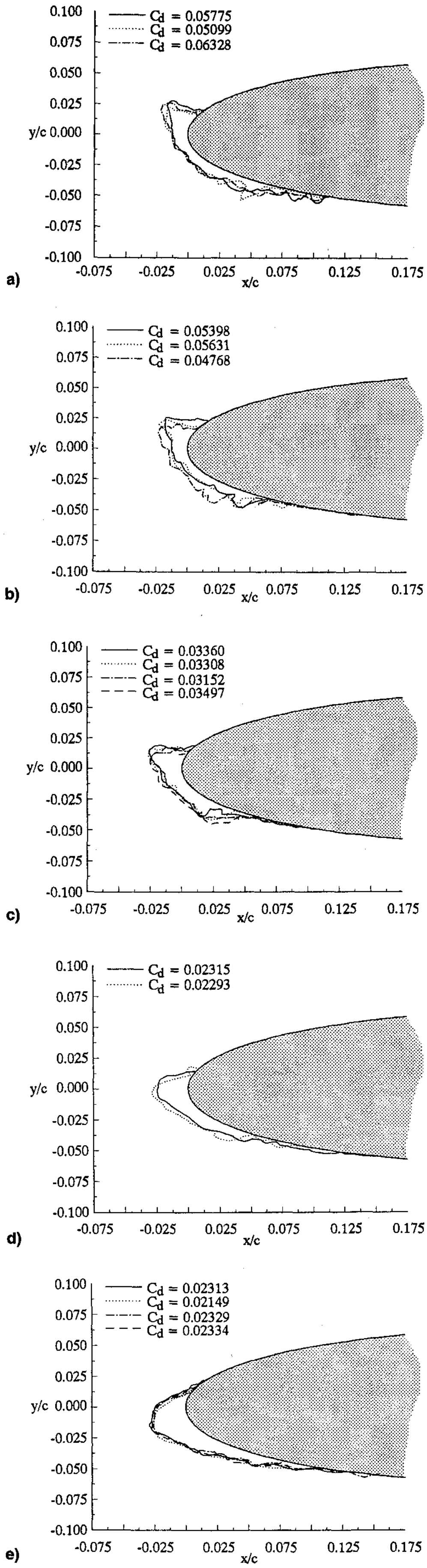

Fig. 1 Repeatability of ice shape and drag coefficient with total air temperature for α = 4 deg, V_∞ = 150 mph, LWC = 1.0 g/m^3, MVD = 20 μm, t = 6 min. T_t = a) 28, b) 25, c) 22, d) 12, and e) −15°F.

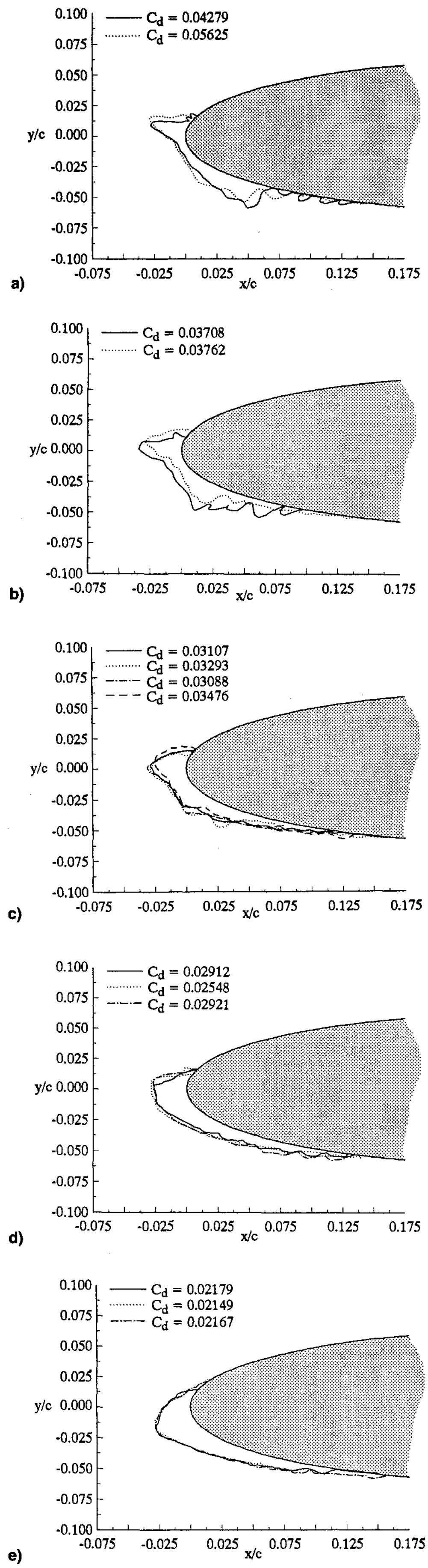

Fig. 2 Repeatability of ice shape and drag coefficient with total air temperature for α = 4 deg, V_∞ = 230 mph, LWC = 0.55 g/m^3, MVD = 20 μm, t = 7 min. T_t = a) 28, b) 25, c) 22, d) 12, and e) −15°F.

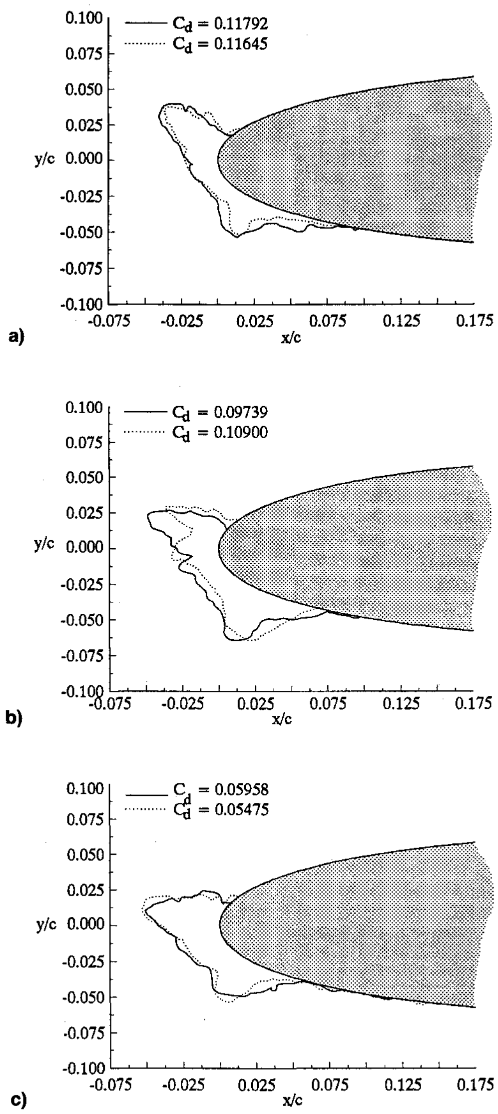

Fig. 3 Repeatability of ice shape and drag coefficient with total air temperature for α = 4 deg, V_∞ = 150 mph, LWC = 1.0 g/m³, MVD = 20 μm, t = 12 min. T_t = a) 28, b) 25, and c) 22°F.

gimes. The test conditions can be divided into two groups: 1) low airspeed and high LWC, and 2) high airspeed and low LWC. Water droplet size was held constant for both groups. Airspeed, LWC, and spray time were selected so that both groups would have the same water intercept (i.e., airspeed × LWC × spray time = const).

The low airspeed, high LWC conditions were run for both 6- and 12-min ice accretion times to investigate the effect of spray time on the repeatability of the ice shape. Test conditions for both spray times are listed in Table 1.

A few tests were also performed with LWC varying from 1.0 to 1.8 g/m³ to determine if LWC affected the repeatability of the ice shape. The conditions for these tests are shown in Table 2.

Test Methods

A typical test procedure for icing runs is listed below:

1) The model angle of attack was set.

2) The target airspeed and total temperature were set.

3) The spray system was adjusted to the desired MVD and LWC.

4) The spray system was turned on for the desired spray time.

5) The tunnel was brought down to idle and the frost beyond the ice accretion was removed.

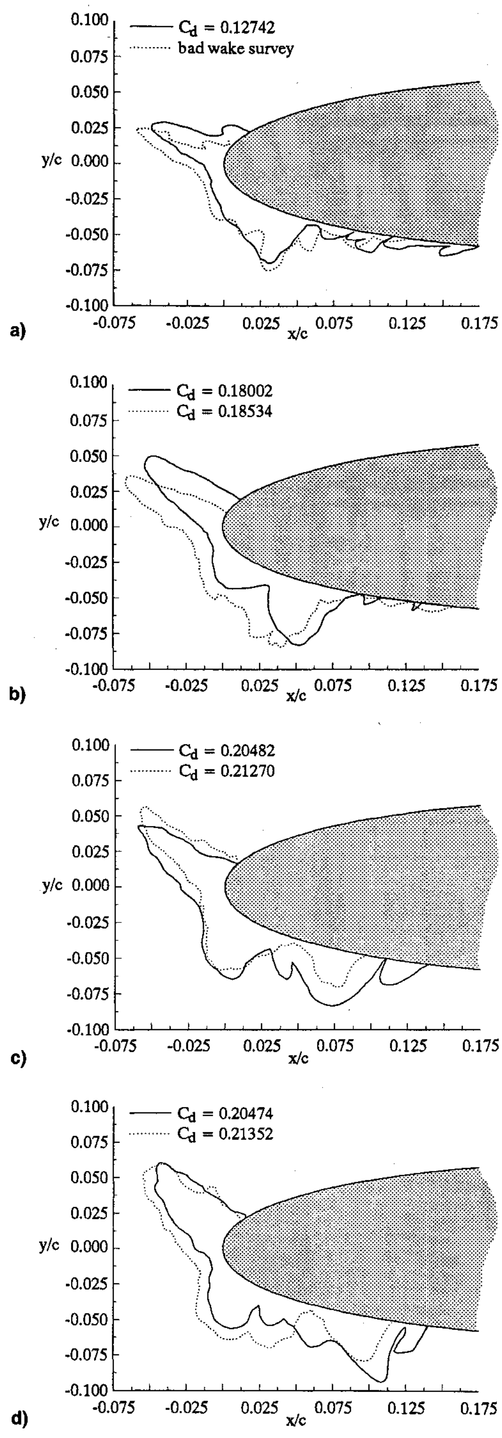

Fig. 4 Repeatability of ice shape and drag coefficient with liquid water content for α = 4 deg, V_∞ = 230 mph, T_t = 22°F, MVD = 30 μm, t = 6 min. LWC = a) 1.0, b) 1.3, c) 1.6, and d) 1.8 g/m³.

6) The wake survey was traversed across the airfoil wake with the tunnel at the target airspeed.

7) The tunnel was brought down to idle again for ice shape tracings and photographs.

8) The airfoil was then cleaned and the tunnel conditions set for the next data point.

To record the ice shape, a heated metal template was used to melt the ice, and the shape was manually traced onto a cardboard template. Ice shape tracings were made at three spanwise locations for each icing run.

Drag Wake Survey

The section drag at the midspan of the airfoil was calculated from total pressure profiles measured by a pitot-static wake

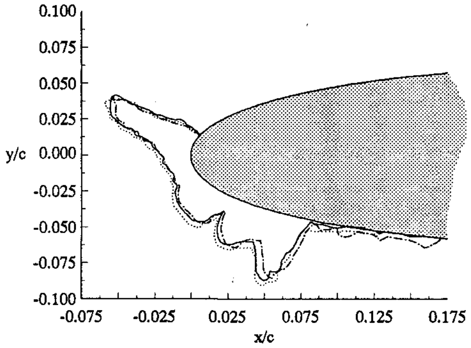

Fig. 5 Comparison of ice shape taken by three data takers (α = 4 deg, V_∞ = 230 mph, T_t = 22°F, LWC = 1.3 g/m³, MVD = 30 μm, t = 6 min).

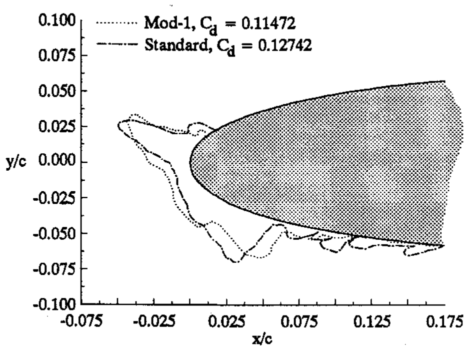

Fig. 6 Comparison of ice shape obtained from standard and mod-1 nozzles for α = 4 deg, V_∞ = 230 mph, T_t = 22°F, LWC = 1.0 g/m³, MVD = 30 μm, t = 6 min.

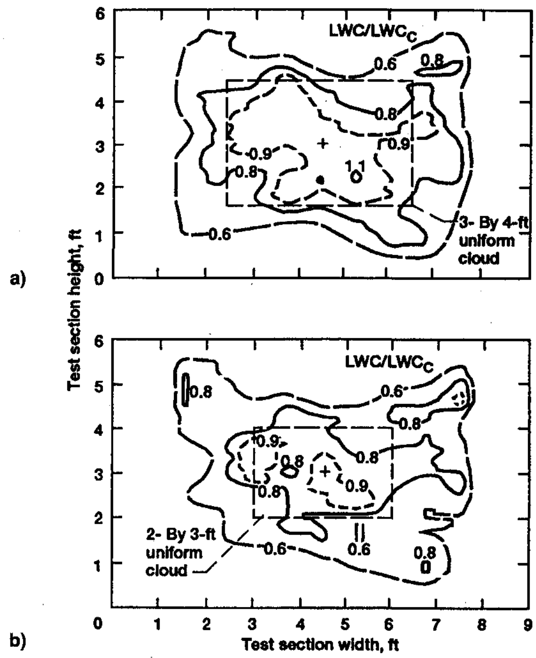

Fig. 7 Contour maps of LWC distribution in NASA Lewis IRT test section (from Ref. 3): a) standard and b) mod-1 nozzles.

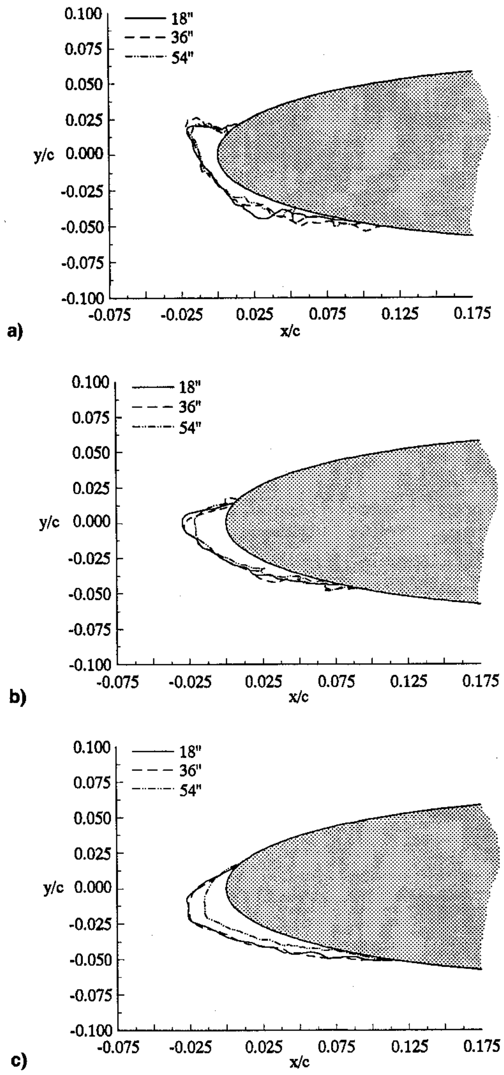

Fig. 8 Spanwise variation of ice shape with standard nozzles (α = 4 deg, V_∞ = 150 mph, LWC = 1.0 g/m³, MVD = 20 μm, t = 6 min). T_t = a) 28, b) 12, and c) −15°F.

survey probe. The method for reducing the data is described in Ref. 2. The wake survey probe was positioned two chord lengths downstream of the airfoil. The wake surveys were made only when the spray cloud was turned off. During sprays, the probe was kept behind a shield to prevent any ice accretion on the tip of the probe. The wake probe was mounted on an automatic traverse system, and the traversing speed was adjustable.

The data from the wake survey was stored by the Escort system that was developed at the NASA LeRC for storing, analyzing experimental data from various facilities at the center. A separate program was used to further analyze the wake data to get wake profiles and drag coefficient.

Results and Discussion

This section contains a discussion of the test results including the repeatability of the ice shape and resulting drag data.

Effect of Air Temperature on Repeatability of Ice Shape and Drag

Results are presented here for typical glaze, rime, and transition ice. The airspeed was set at 150 mph and the accretion time was 6 min. The resulting ice shape showed typical glaze ice accretion with the characteristic upper ice horn at the total air temperatures of 28, 25, and 22°F. At −15°F, the ice shape was that of typical rime ice. The ice accretion at 12°F displayed a transition shape.

Figure 1 shows ice shapes traced at the midspan and corresponding drag coefficients for the low-airspeed, high-LWC case (150 mph, 1.0 g/m³). At each temperature, ice shape tracings from all repeat runs are overlaid. The repeatability of the ice shape is fairly good at 28°F (Fig. 1a), 25°F (Fig. 1b), and 22°F (Fig. 1c), except the third run at 25°F, where thicker ice is seen. Ice horn growth and the thickness of ice

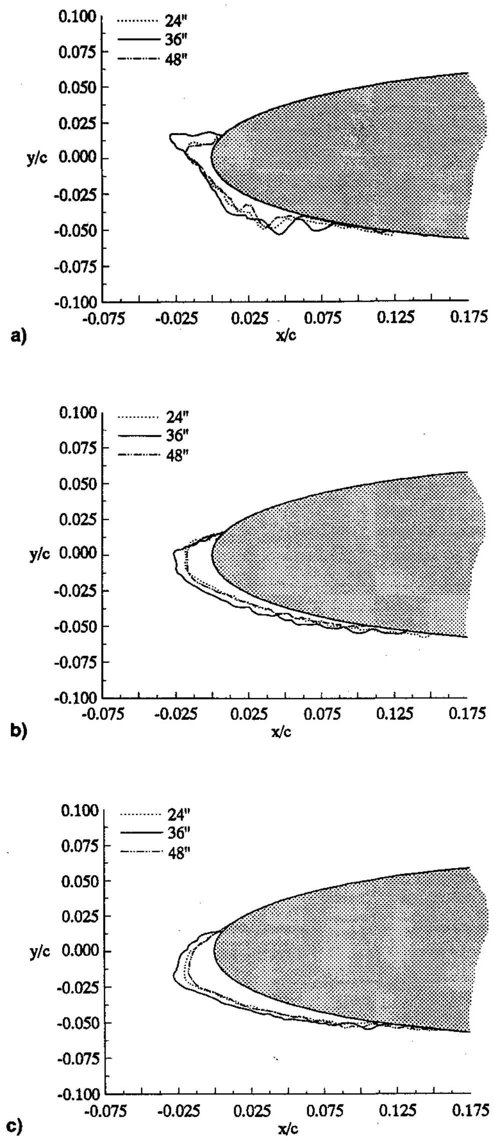

Fig. 9 Spanwise variation of ice shape with mod-1 nozzles (α = 4 deg, V_∞ = 230 mph, LWC = 0.55 g/m³, MVD = 20 μm, t = 7 min). T_t = a) 28, b) 12, and c) −15°F.

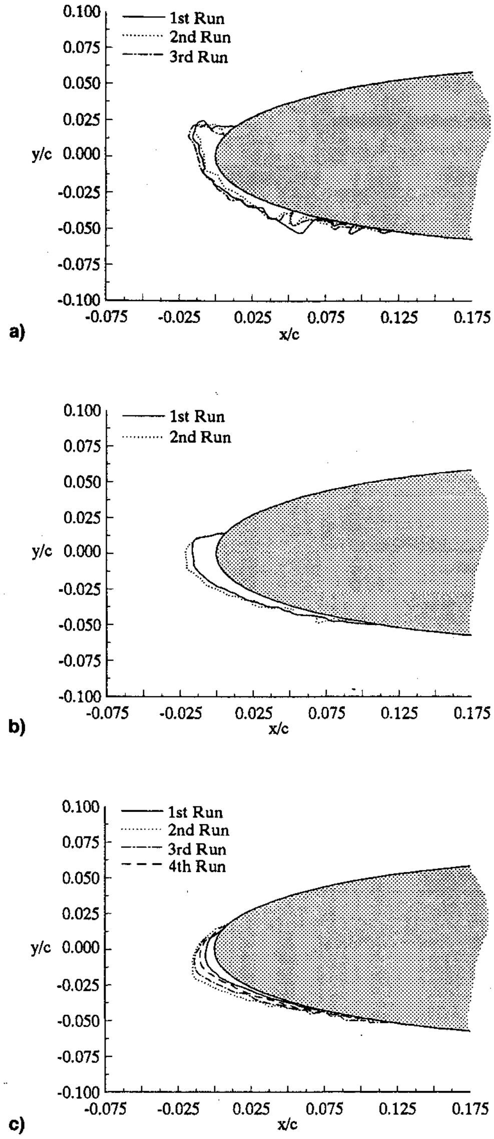

Fig. 10 Repeatability of ice shape at the top (z = 54 in.) span location (α = 4 deg, V_∞ = 150 mph, LWC = 1.0 g/m³, MVD = 20 μm, t = 6 min). T_t = a) 28, b) 12, and c) −15°F.

repeat well at all three temperatures. Icing limits at the upper and the lower surface show good repeatability. The repeatability of the ice shape was best at the lowest temperature, −15°F (Fig. 1e). Overall repeatability of the drag coefficient was typically within the experimental variation for a clean airfoil.

Figure 2 presents data for the high-airspeed, low-LWC case. For these tests, the airspeed was 230 mph and the LWC was 0.55 g/m³. These values give the same water intercept as the 150-mph, 1.0-g/m³ case of Fig. 1. Water droplet size was again kept constant at 20 μm. The resulting ice shape is that of glaze ice at 28°F (Fig. 2a), 25°F (Fig. 2b), and 22°F (Fig. 2c), even though the upper horn is not as dominant as for the 150-mph, 1.0-g/m³ case. The ice shape at 12°F (Fig. 2d) is more of that of rime ice, and the ice shape is that of typical rime ice at −15°F (Fig. 2e). As seen for the 150-mph, 1.0-g/m³ case, the repeatability of the ice shape is fair at 28, 22, and 12°F, and very good at −15°F. The repeatability of the ice shape at 25°F is not as good as that with other temperatures. The variation of the drag coefficient is comparable with that of the 150-mph, 1.0-g/m³ case.

The IRT has two sizes of nozzles: 1) standard and 2) mod-1, with the only difference being the diameter of the orifice tube. The mod-1 nozzles are used to produce a lower test section LWC than the standard nozzles for the same spray pressures. Standard nozzles were used for the 150-mph, 1.0-g/m³ case, whereas mod-1 nozzles were used for the 230-mph, 0.55-g/m³ case. Both sets of nozzles show similar repeatability of the ice shape for the temperature range tested.

Effect of Spray Time on Repeatability of Ice Shape and Drag

The effect of spray time on the repeatability of the ice shape was studied by extending the spray time to 12 minutes for the 150-mph, 1.0-g/m³ case. Since the repeatability of rime ice was shown to be very good for a spray time of 6 min (Fig. 1), only the glaze ice conditions were tested. Figure 3 shows good repeatability in the ice shape at 28°F (Fig. 3a) and 22°F (Fig. 3c). As with the 6-min-spray tests, the repeatability at 25°F (Fig. 3b) is not as good as that with the other temperatures. The repeatability of drag coefficient is fairly good for all three temperatures.

Effect of Liquid Water Content on Repeatability of Ice Shape and Drag

The effect of LWC on the repeatability of the ice shape and drag is shown in Fig. 4. LWC used for this part of the

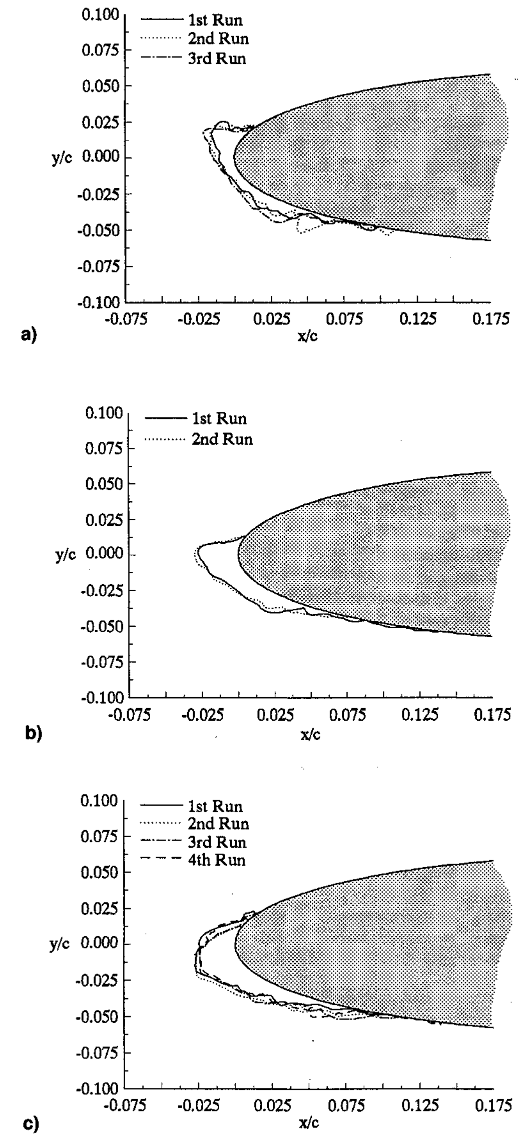

Fig. 11 Repeatability of ice shape at the bottom (z = 18 in.) span location (α = 4 deg, V_∞ = 150 mph, LWC = 1.0 g/m^3, MVD = 20 μm, t = 6 min). T_t = a) 28, b) 12, and c) −15°F.

test was fairly high, ranging from 1.0 to 1.8 g/m^3. The spray time was 6 min, which resulted in fairly large accretions of ice for all conditions. The total air temperature was set at 22°F, which produced typical glaze ice. The airspeed was 230 mph and the MVD was 30 μm.

Figure 4 gives results for 1.0, 1.3, 1.6, and 1.8 g/m^3. The ice shapes from the first and the second runs were not aligned for any of the four LWCs. Although the ice shapes show a shift between two runs at each condition, the ice shapes look very similar. Drag data also shows good repeatability; this suggests that the ice shapes did in fact repeat well. The shift was probably caused by the fact that all the first runs were traced by one person and all the second runs were traced by another person.

An exercise was performed to document the magnitude of the variation in the ice shape due to the human elements involved during ice shape tracings. An ice shape at the midspan from one icing run was traced by three individuals; the resulting shapes are shown in Fig. 5. Some of the details in the ice shape varied with data takers, and a minor shift was also seen. However, overall ice shapes agreed well and the magnitude of the variation in the ice shape was within the experimental repeatability. This kind of agreement is typical and the variation seen in the LWC-effect case does not normally occur.

Effect of Spray Nozzle on Repeatability of Ice Shape and Drag

Some conditions in the IRT operating envelope can be obtained by either standard or mod-1 nozzles. Ice shapes for the LWC = 1.0 case were obtained using both nozzles to study whether a common icing condition could be effectively duplicated by either set of nozzles. Figure 6 shows the result, and the ice shapes show good agreement. The variance in drag coefficient was no greater than typically seen for other repeat tests reported here, and only slightly higher than variation in typical dry-airfoil drag coefficients.

Effect of Cloud Uniformity on Spanwise Variation in Ice Shape

The uniformity of the spray cloud in the IRT has been documented in Ref. 3. Contour maps of the LWC in the test section are shown in Fig. 7 (from Ref. 3) for the standard and mod-1 nozzles. The area of uniform cloud obtained using the mod-1 nozzles is smaller than that using the standard nozzles. In order to document spanwise variation in the ice accretion within the uniform spray cloud, multiple tracings along the span were taken with each icing run.

Figure 8 shows the spanwise variation of the ice shape with the standard nozzles. Figure 8a is for a temperature of 28°F, 8b for 12°F, and 8c for −15°F, covering glaze, transition, and rime ice. Ice shape tracings were taken at the three spanwise locations, 18, 36, and 54 in., measured from the tunnel floor. The 18- and 54-in. locations represent the bottom and top boundaries of the uniform test section cloud for the IRT standard nozzles shown in Fig. 7a. The results show close agreement in the ice shape between the 36- and 18-in. locations, but slightly lower ice accretion at the 54-in. location. This result is consistent with the LWC distribution shown in Fig. 7a, where the LWC varies little from the lower boundary of the uniform cloud to the center, but begins to decrease near the top.

Figure 9 shows the ice shapes with the mod-1 nozzles at three spanwise locations: 24-, 36-, and 48-in. from the floor. The top (z = 48 in.) and bottom (z = 24 in.) locations represent the boundaries of the uniform test section cloud shown in Fig. 7b. Results for temperatures of 28°F (Fig. 9a), 12°F (Fig. 9b), and −15°F (Fig. 9c) are shown. At all three temperatures, the thickest ice is seen at the midspan (36 in.). At the top and bottom locations, the ice accretion is very similar in both mass and shape. This result is again consistent with the LWC distribution shown in Fig. 7b, where the LWC is approximately equal at the top and bottom of the uniform test section cloud map.

In order to validate the observations made above, the repeatability of the ice shape at the top and the bottom spanwise locations was also investigated. Figure 10 shows the comparison of the ice shape from repeat runs at the top location (z = 54 in.) with the airspeed of 150 mph. The repeatability is good at 28°F (Fig. 10a) and 12°F (Fig. 10b). At −15°F (Fig. 10c), good agreement was shown between the second and the third runs, but agreement was not so good with the other two runs.

The repeatability of the ice shape at the bottom location (z = 18 in.) with the airspeed of 150 mph is shown in Fig. 11. The repeatability is good at all temperatures. The repeatability of the ice shape at the top and bottom locations for 230 mph was also good at all temperatures. Generally, the repeatability of the ice shape at top and bottom locations was as good as the repeatability at midspan (Fig. 1). However, in some cases, the quantity of ice accreted decreased with the distance from the center of the tunnel. Based on these observations, it is recommended that ice shape tracings be made at the midspan for any data purpose.

Concluding Remarks

Tests to investigate the repeatability of the ice shape and resulting drag were performed, and the results were presented. This test program also provided a new database for code validation work. Several findings from the test include the following:

1) The repeatability of the ice shape was fair at near freezing temperatures (28°F), and the repeatability improved as the ice shape changed from glaze to rime ice (−15°F). The repeatability of the ice shape was very good at −15°F.

2) An increase in the airspeed did not affect the repeatability in the ice shape and drag.

3) The accretion time did not affect the repeatability of the ice shape.

4) The repeatability of the ice shape did not deteriorate with LWC.

5) Both standard and mod-1 nozzles gave the same results for a common icing condition.

6) All the major characteristics in the ice shape were preserved along the span within the uniform test section cloud. The quantity of ice accreted decreased with distance from the center of the tunnel for the mod-1 nozzles. For the standard nozzles, the quantity of ice accreted at the mid- and the bottom-span locations was very close, but less accretion of ice was seen at the top-span location.

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