LARGE VERSUS SMALL DROPLET ICING

8.5

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1. Introduction

Ice accumulation on aircraft surfaces depends on many aerodynamic and meteorological variables listed in Table 1. Engineers at the National Aeronautics and Space Administration (NASA) John H. Glenn Research Center have developed LEWICE 2.2.2 software that evaluates the thermodynamics of supercooled droplets as they impinge on a body given these inputs and computes the resulting ice shape. The aerodynamic performance changes can be analyzed using computational fluid dynamics (CFD) software which solves the Navier-Stokes equations for the resulting airflow. McCann and Kennedy (2000) introduced the Percent Power Increase (PPI), which can be computed from CFD software, as a simple way to quantify the performance change.

Table 1. Aerodynamic and meteorological variables available to input into LEWICE 2.2.2

- Body shape
- Exposure time
- Droplet size distribution
- Chord length
- Angle of attack
- Flight speed
- Liquid water content
- Air temperature

Lift and drag are functions of the aircraft's speed (*V*)

$$Lift = C_L A \frac{\rho V^2}{2}$$

$$Drag = C_D A \frac{\rho V^2}{2}$$

where ρ is the air density, *A* is the cross sectional area of the aircraft component, and C_L and C_D are coefficients of lift and drag respectively. In order to maintain speed and altitude, the new thrust (power) is

$$Thrust_{iced} = Thrust_{clean} \frac{C_{L:clean}}{C_{L:iced}} \frac{C_{D:iced}}{C_{D:clean}}$$

where the subscripts *clean* and *iced* indicate conditions before and after ice accumulation. Thus

$$PPI \times .01 = \frac{Thrust_{iced}}{Thrust_{clean}} - 1 = \frac{C_{L:clean}}{C_{L:iced}} \frac{C_{D:iced}}{C_{C:clean}} - 1$$

To help Aviation Weather Center (AWC) forecasters understand icing's effects on aircraft performance, the AWC obtained the LEWICE 2.2.2 software (Wright 2002) and XFOIL 6.94, CFD software from the Massachusetts Institute of Technology (Drela and Youngren 2001). Several hundred tests were performed in the following manner: Holding seven of the eight variables constant, the remaining variable was changed over its expected range and input into LEWICE. Upon reaching the final ice shape, the body was input into XFOIL which computed iced C_L and C_D . Knowing clean C_L and C_D , PPI was easily computed.

While the overall results are informative, one result was suprising. Although research has suggested that droplets in the drizzle size range (50-500 µm) are the most hazardous kind to encounter (Politovich 1989), for a given liquid water content and air temperature, the PPI at 20 µm droplet size typically was at least as large as any other size. This paper shows output from several representative experiments, including two scenarios on the data for the 1995 Roselawn ATR-72 icing accident.

2. Input variables

The bulk of the test runs were on a 1.5 m NACA 23012 airfoil, 90 m sec^{-1} air speed, zero angle of attack, and 5 minutes accumulation. These represent a Beechcraft King Air at typical cruise conditions. Except as noted, all figures were generated with these inputs. Input air temperatures (T) ranged from -1C to -25C; liquid water contents (LWC) ranged from 0.1 g m^{-3} to 2.0 g m^{-3} , and median volume droplet diameters (MVD) ranged from 10 µm to 1000 µm.

Two issues arise concerning droplet size inputs into LEWICE. 1) Droplet sizes tend to become more disperse as the median increases, however Wright (2002) suggests that icing shapes do not vary much from a monodispersed distribution compared with distributions with a wider spread but an equal median. 2) LEWICE was validated with wind tunnel results only with droplet sizes between 15 µm and 50 µm, but results with sizes up to 270 µm are included in the code. With larger droplet sizes LEWICE evaluates the approximate ice shape. While the detailed shape may be important, lift and drag are integrated quantities which do not depend greatly on the detailed shape (Wright and Potapczuk 1996).

XFOIL computes the lift and drag coefficients for each LEWICE-computed ice shape. The PPI can be determined using the relationship above from the iced and clean aerodynamic coefficients. (clean C_L = .1592 and clean C_D = .01060).

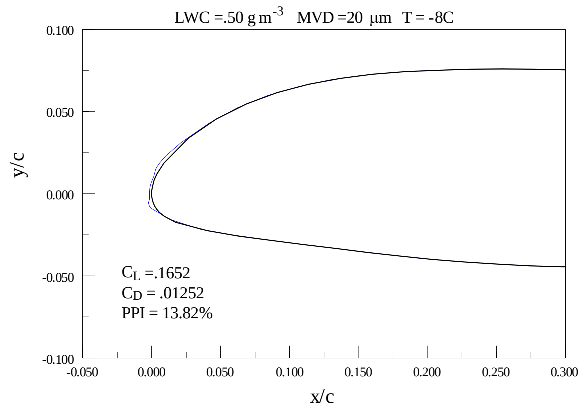

Figure 1. LEWICE ice shape for LWC = .50 g m^{-3}, MVD = 20 µm, and T = -8C. Aircraft performance data are in the lower left.

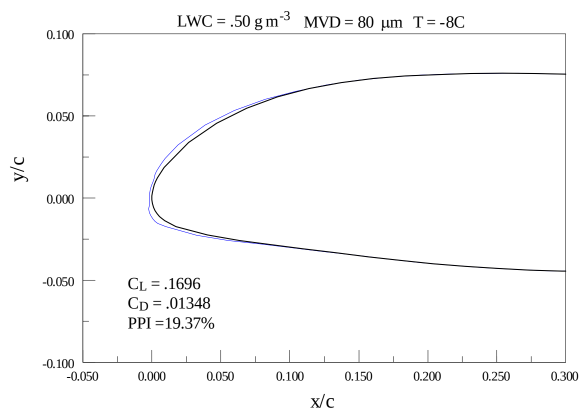

Figure 2. Same as Figure 1 except MVD = 80 µm.

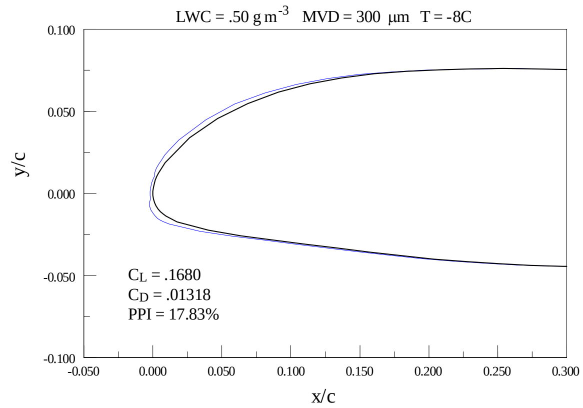

Figure 3.Same as Figure 1 except MVD = 300 µm.

3. The effect of droplet size

Increasing the droplet size causes the catch efficiency to increase, thus more ice accumulates (Wright and Potapczuk 1996). Figures 1-3 show visually examples of ice shapes for LWC = .50 g m^{-3} and T = -8C with three different MVD. In each figure x/c and y/c are coordinates normalized by the airfoil chord length. The shapes within x/c < .02 are similar, but with increasing MVD, the excess ice accumulates further back from the leading edge, as much as x/c = .15 for MVD = 300 µm. Furthermore, the excess accumulation conforms with the airfoil shape so there is little perceivable extra performance loss with the extra ice. For a given LWC and T the shape near the leading edge seems to determine performance loss. Figure 4 shows the PPI for LWC = .75 g m^{-3} for three temperatures, illustrating the response for various MVD. The highest PPI occurs with the 20 µm droplets except for T = -20C where the peak is in the 40-100 µm range. In overall test runs, this exception generally occurs with LWC > .50 g m^{-3} and T < -12C, atmospheric conditions likely encountered only in thunderstorms. For “general” icing droplet size makes little difference in PPI.

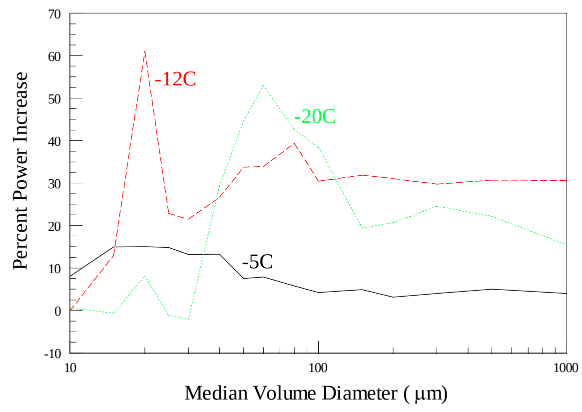

Figure 4. PPI as a function of MVD for three different temperatures.

Many "hazardous" icing encounters in the literature are of longer duration accumulation than 5 minutes. To test droplet size and duration, LEWICE was run with two droplets sizes, 20 µm and 200 µm, but identical LWC = .30 g m^{-3} and T = -5C for 45 minutes. LEWICE was stopped at intervals to assess the ice accumulation and PPI.. Figures 5 and 6 show that after 30 minutes, ice accumulation is very different for the different droplet sizes, but the PPI values are almost the same. Figure 7 shows the PPI increase with time for each size. Initially, the PPI is greater for the 200 µm exposure, but after 20 minutes the values are nearly equal. Before 20 minutes, with just a few minutes more exposure, the 20 µm PPI is as great as the 200 µm PPI.

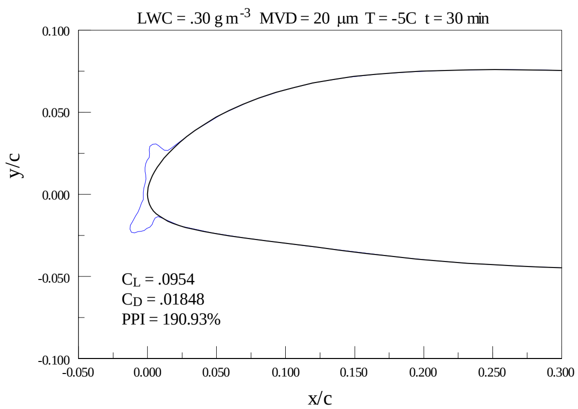

Figure 5. LEWICE ice shape for LWC = .30 g m^{-3}, MVD = 20 µm, T =-5C, and time = 30 minutes. Aircraft performance data are in the lower left.

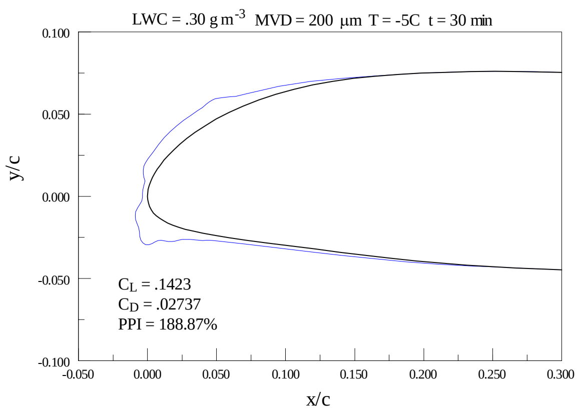

Figure 6. Same as Figure 5 except for MVD = 200 µm.

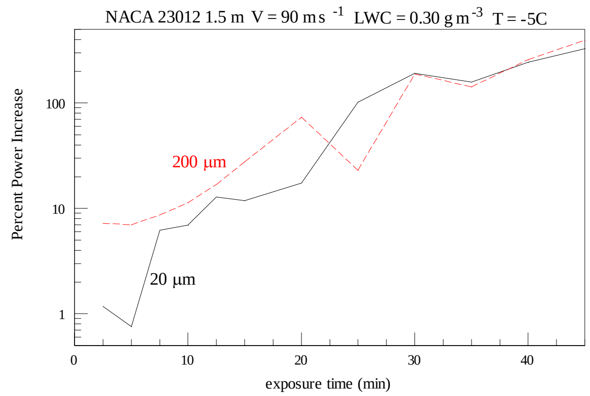

Figure 7. PPI as a function of exposure time for two MVD.

This result is relevant to the 31 October 1994, Roselawn, IN, ATR72 accident that has spurred the awareness of large droplet icing (Marwitz et al. 1997). In that case the aircraft exposure to supercooled water was 24 minutes. LEWICE was run for an ATR72 airfoil with aerodynamic input prescribed in the National Transportation Safety Board (1996) report and two meteorological scenarios taken from Marwitz et al. (1997). Figures 8 and 9 show the ice accumulation, and Table 2 compares the results.

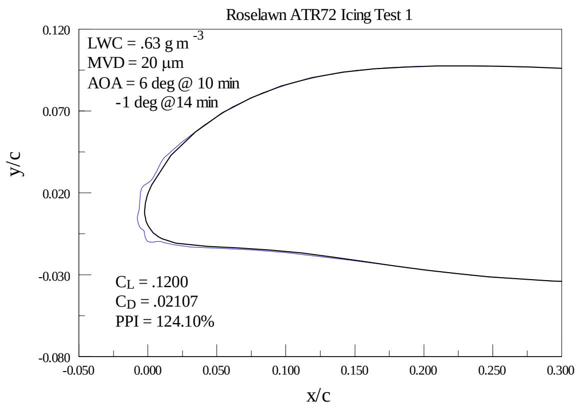

Figure 8. LEWICE ice shape for Test 1 in Table 2.. Aircraft performance data are in the lower left.

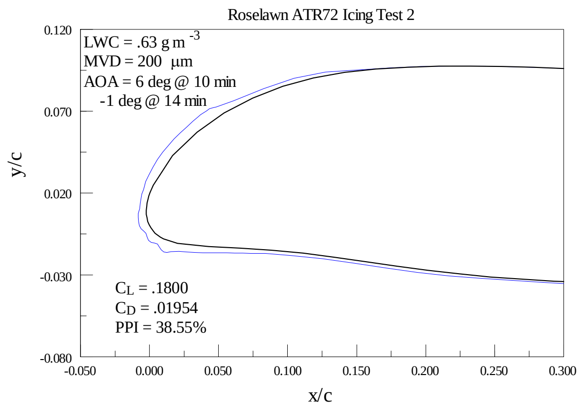

Figure 9. Same as Figure 8 except for Test 2 in Table 2..

Table 2. LEWICE test runs for the Roselawn, IN, ATR72 accident (1.6 m NACA 43013 , 80 m sec^{-1} airspeed, T =-3.7C, LWC =.63 g m^{-3}, Angle of attack [AOA] = 6 deg @ 10 min -1 deg @ 14 min).

Test	MVD(µm)	PPI
1	20	124.10%
2	200	38.55%

Interestingly, similar tests with only a 5 minute exposure show negative PPI for both 20 µm and 200 µm droplets. The LEWICE computations in this case suggest that the icing problem for the ATR72 was a prolonged exposure to high LWC conditions.

4. Discussion

Icing intensity definitions in the *Aeronautical Information Manual*, as defined in Table 3 and dating from the 1960s, intend to inform pilots how quickly they need to react to ice accumulation. It seems reasonable that when the PPI reaches a certain value, activation of deicing/anti-icing equipment would be necessary. The LEWICE experiments show a logarithmic PPI increase with time (Figure 7, for example) such that almost any icing encounter will eventually reach a PPI threshold for equipment activation in less than one hour. But if it is safe to fly in light icing for less than one hour without equipment activation, as implied in its definition, then light icing would be very rare. The problem is the large time difference between “short” and one hour. If the phrase “over one hour” were removed from the light definition, then “light icing” fits comfortably between trace and moderate.

Table 3. Icing intensity definitions

Trace – Ice becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. Not hazardous even if no deicing/anti-icing equipment is used, unless encountered for an extended period of time – over one hour.

Light – Rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation.

Moderate – Rate of accumulation is sufficient that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

Severe – Rate of accumulation is so great the deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

Currently in the United States, only moderate and severe icing are considered hazardous with AIRMETs and SIGMETs officially issued to advise pilots of those hazards. Since long exposures in light icing conditions can be dangerous, pilots should also be informed of light icing areas if only to make them aware of the potential for disaster.

Although aircraft performance loss does not appear to be dependent on droplet size, a pilot may exacerbate the loss by deicing in a large droplet environment. This is because deicing eliminates ice only along the leading edge. Because splashing allows ice to accumulate further back from the leading edge, ice may remain aft of the boots after deicing. The larger the droplets, the bigger the problem. Figures 10 and 11 illustrate that. Before deicing, the performance loss was probably manageable. After deicing, the remain ice shape exacts a large performance toll. The performance loss in freezing rain described by Bernstein et al. (1999) may have happened because of deicing. Pilots know of this problem and hopefully are aware when they fly in a large droplet environment.

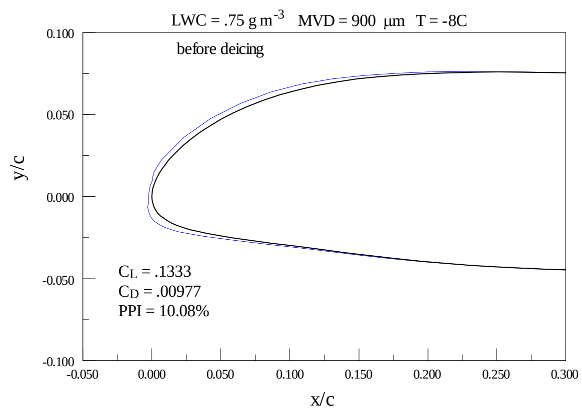

Figure 10. LEWICE ice shape for LWC = .75 g m^{-3}, MVD =900 µm, and T =-8C before deicing.

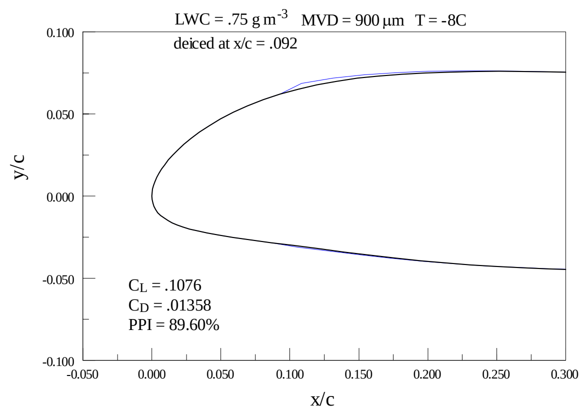

Figure 11. Same as Figure 10 except airfoil is deiced at x/c =.092.

5. Conclusions

These LEWICE experiments have some obvious limitations. One trouble is that software airfoils are two-dimensional and real airfoils are three-dimensional. A second problem is that although lift occurs with the wing, all aircraft components are subject to drag, so the drag coefficient change may be different than just considering the wing.

Nevertheless, the LEWICE experiments show that liquid water content and temperature are the primary meteorological variables that determine aircraft performance loss due to icing. For a given LWC and T, most environments with MVD > 50 µm were no worse than environments with MVD = 20 µm. The results suggest that large droplet ice accumulation may be overemphasized. This is good news for forecasters because it is one less variable to consider.

References

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