Collaborative Experiments and Computations in Aircraft Icing

Richard E. Kreeger[1]

NASA Glenn Research Center, Cleveland, OH, 44135

Andy Broeren[2]

NASA Glenn Research Center, Cleveland, OH, 44135

The formation of ice over lifting surfaces can affect aerodynamic performance. The ability to predict ice accumulation and the resulting degradation in vehicle performance is essential to determine the limitations of aircraft in icing encounters. The consequences of underestimating performance degradation can be serious and so it is important to produce accurate predictions, particularly for severe icing conditions. The simulation of ice accretion is a challenging multidisciplinary problem that requires close collaboration between the computational and ground test communities. This paper describes three recent case studies and the lessons learned through collaborative experiments and computations in aircraft icing- one for large commercial transports, one for rotorcraft, and one dealing with icing on regional jets.

I. Introduction

The formation of ice over lifting surfaces can affect aerodynamic performance. The ability to predict ice accumulation and the resulting degradation in vehicle performance is essential to determine the limitations of aircraft in icing encounters. The consequences of underestimating performance degradation can be serious and so it is important to produce accurate predictions, particularly for severe icing conditions. The effects of icing on vehicle aerodynamics can be obtained from experimental testing, computational tools, or flight testing. The experimental tools needed for icing analysis include icing wind tunnels, aerodynamic wind tunnels, scaling methods, ice shape measurement methods, and model construction methods. Wind tunnels offer a controlled environment but sometimes not all the dimensionless parameters can be matched exactly. Computational tools which are needed typically include ice accretion codes, airfoil design codes and computational fluid dynamics (CFD) codes. CFD is generally considered the most cost-effective, and is the only method which can simulate all geometries and all flight conditions, but its accuracy depends on the quality of the grid and the ability of the flow solver (including turbulence model) to capture all of the relevant physics. Flight testing is the most realistic, but also the most expensive.

Icing codes are constantly being improved to analyze the next generation of aircraft, while simultaneously being evaluated based on the previous generation. The icing analyses of a large next generation commercial transport, or a turbofan engine at high altitude under glaciated cloud conditions, or a small unmanned aerial system flying beneath the standard Appendix C icing cloud[1] minimum altitude (i.e. 500 ft above sea level), or a next-generation helicopter with the complex flowfield of counter-rotating blades stretch the capability of current icing codes. The range and spectrum of new vehicles and new markets which are emerging, for both conventional and non-conventional configurations, require extended and improved tool capability.

Ground test facilities are constantly being pushed as well- maintaining calibration, improving flow quality, accommodating new test measurement techniques, and expanding the calibrated envelope of test conditions are areas of ongoing need. In addition, there are some test conditions which still cannot be simulated by the facility but due to new missions or new regulatory requirements are now needed.

In recent years, much progress has been made in numerical methods (e.g., CFD, turbulence models, etc.), ground test techniques (e.g., wind tunnel non-intrusive on-body and off-body flow diagnostics, etc.), and flight test

---

[1] Research Aerospace Engineer, Icing Branch, 21000 Brookpark Rd., Associate Fellow, AIAA
[2] Research Aerospace Engineer, Icing Branch, 21000 Brookpark Rd., Associate Fellow, AIAA

techniques (e.g., flight test telemetry miniaturization, etc.). It is not uncommon for results to disagree, and often this is a result of little cooperation and collaboration between the various communities. Other studies[2] not specific to aircraft icing have also proposed that better integration is needed between advanced computer models and improved ground-based measurement techniques, to benefit multiple disciplines. The simulation of ice accretion is a challenging multidisciplinary problem that requires close collaboration between the computational and ground test communities. This paper gives some background and then describes three recent case studies and the lessons learned through collaborative experiments and computations in aircraft icing- one for large commercial transports, one for rotorcraft, and one dealing with icing on regional jets.

II. Background

Icing analysis for aircraft employs a variety of computational tools and experimental test methods. In order to realistically simulate ice growth and determine its aerodynamic impact, these various elements must be pieced together in a validated[3,4] yet robust work path.

Stand-alone ice accretion prediction tools, based on the classical Messinger model, as well as ice accretion integrated with aerodynamics tools, currently exist for many airfoil and aircraft applications. LEWICE is NASA's flagship code for 2-D ice accretion prediction, and it is the core of the 3-D ice accretion tools as well. LEWICE development began in the early 1980's, with the first version released in 1991. Several major updates to the code have been made between 1993 and present day.

LEWICE uses a panel method to determine the flow field over a clean airfoil, then calculates water droplet trajectories from an upstream release point until they impact the surface or bypass the body. Collection efficiency is then determined from the water droplet impact locations within calculated impingement limits. Multiple drop sizes can be considered. A quasi-steady energy and mass balance is performed on each control volume using a time-stepping routine and ice growth normal to the surface is calculated. Density correlations are used to convert ice growth mass into volume. LEWICE also features multi-element airfoil capability, an interface with CFD grid tools, thermal models for anti-icing or de-icing systems, and a limited mixed-phase modeling capability.

LEWICE3D uses a Monte-Carlo-based collection efficiency using droplet impact counts. Trajectories are calculated using an Adams-type predictor-corrector method. Streamlines are calculated using a 4^{th}-order Runge-Kutta integration scheme. The ice growth methodology in LEWICE3D is similar to LEWICE, but uses a single time step approach and requires a steady or time-averaged flow solution. LEWICE3D supports multi-block structured grids, adaptive Cartesian grids, unstructured grids, and panel-based binary-tree grids. A strip approach using a modified version of the LEWICE routine is applied along streamlines to determine ice growth. An integral boundary layer technique can be used to generate the heat transfer coefficients.

Tool development issues continually arise as new applications are developed. Perhaps the most important of these is whether to develop a tool as open-source or using centralized development and distribution. Strictly speaking the codes must demonstrate the capability of computing collection efficiency and ice shapes. Developers must assess whether results are accurate enough, or whether additional validation is needed. High quality validation data is a key driver of tool development and community acceptance. Validation requires testing in an icing tunnel, so that the ice accretion predictions could be evaluated. There is a role for both publicly-available and proprietary validation data, as long as the data are research quality.

Just a few examples: more data are needed of three-dimensional ice shapes on three-dimensional geometries, of warm glaze ice with surface water, and of ice accretion under supercooled large droplet (SLD) conditions. Developers must contend with validation using data from different facilities, for example, comparing ice shapes obtained in the National Aeronautics and Space Administration (NASA) Glenn Icing Research Tunnel (IRT) with ice shapes obtained in the Penn State Adverse Environment Rotor Test Stand (AERTS).

Icing ground testing has its own unique complexities as well. Scaling methods for ice accretion tests can be more complex than the geometric, Mach number and Reynolds number scaling of typical aerodynamics testing. For some vehicles, for example rotorcraft and engines, there are additional complexities beyond condition scaling, such as azimuthal-averaging or flow matching. Furthermore, scaling of thermal ice protection systems and altitude scaling are also sometimes required. Cloud conditions in an icing wind tunnel require calibration of the cloud's liquid water content (LWC) and median volume diameter (MVD) and flow quality can be affected by a disparate set of parameters, including the outside humidity or the amount of particulates in the water. The unique issues associated with conducting aerodynamic tests in icing wind tunnels are closely related to cloud uniformity, or the lack of cloud near the walls. The high degree of turbulent mixing typically present in an icing wind tunnel (to help create a more uniform icing cloud) provides poor flow quality compared to aerodynamic tunnels, so the use of an icing wind tunnel for making aerodynamic measurements requires a detailed understanding of the facility limitations relative to the test objectives.

In addition, icing wind tunnel models tend to be larger because they are operated over a smaller angle of attack range. Aerodynamic tunnel models tend to be much smaller since measurements are made of a large range of angle of attack. Whatever turns out to be the resolution of these issues, ice accretions measured in an icing wind tunnel are typically reproduced (cast from molds, 3D lasers scans, or other methods) and the aerodynamic measurements have to be conducted in a different dry-air wind tunnel with lower turbulence. In a research environment, specially-designed and built test hardware will tend to lead to better results compared to retro-fitting flight hardware.

There are also areas of measurement techniques which continue to need further study. These include off-body measurements (for example, in active flow control technology), high-speed video resolution (comes up in droplet splashing/breakup), a standardized method of measuring ice adhesion (for the evaluation of icephobic material prototypes), and dynamic stall. The remote measurement of melt ratio and droplet temperature are also key technical challenges.

III. Discussion

Simulating aircraft icing, whether experimentally or computationally, involves two separate elements: ice accretion and iced aerodynamic performance. Both have their own set of additional difficulties when compared to traditional clean aircraft. With ice accretion, for example, there is a need to update the particle collection efficiency and subsequent ice growth, which occur at longer time scales when compared with the aerodynamic flow field. With iced aerodynamics, there is a need to address complex geometries with multiple ice roughness scales that are typically not encountered in most aerodynamic simulation scenarios.

All of these issues require collaborative research involving both computational and experimental components. The following section describes three different research efforts and the lessons learned through collaborative experiments and computations in aircraft icing- ice accretion prediction on large swept wings, rotor blade icing, and the aerodynamics of a business jet airfoil with leading edge ice accretion.

1. Ice Accretion Prediction on Large Swept Wings

Ice accretion and its resulting aerodynamic effects on three-dimensional swept wings is a complex phenomenon. Flight testing a large commercial transport (any aircraft, actually) represents a significant cost, so the need to test ice protection systems under controlled conditions must be conducted in an icing wind tunnel. The use of CFD for icing applications also plays an important role in aircraft certification and the design of ice protection systems.

Large-scale, three-dimensional swept wings presented a particular challenge to the existing LEWICE analysis methods. An example of the highly three-dimensional ice shapes which can occur on swept wings is shown in Figure 1. Recently, NASA, the Federal Aviation Administration (FAA), ONERA, Boeing and the Universities of Illinois and Washington embarked on a collaborative research effort to address these technical challenges. The effort incorporated ice-accretion experiments, iced aerodynamic experiments and computational simulations[5,6].

First, the team selected a representative wing model and identified how to generate ice shapes. A baseline swept-wing reference geometry, based on the Common Research Model (CRM), was utilized. The CRM is a generic representative of a state-of-the-art wide-body commercial transport aircraft. A key feature of selection was the contemporary transonic supercritical wing design. Additional factors in making this selection were the prior aerodynamic testing that had been conducted in various wind tunnels, application of CFD tools for applied validation studies, the publicly-available wing geometry, and unrestricted distribution of the wing geometry. Geometric features considered included span, mean aerodynamic chord, wing area, aspect ratio, taper ratio, and sweep angle.

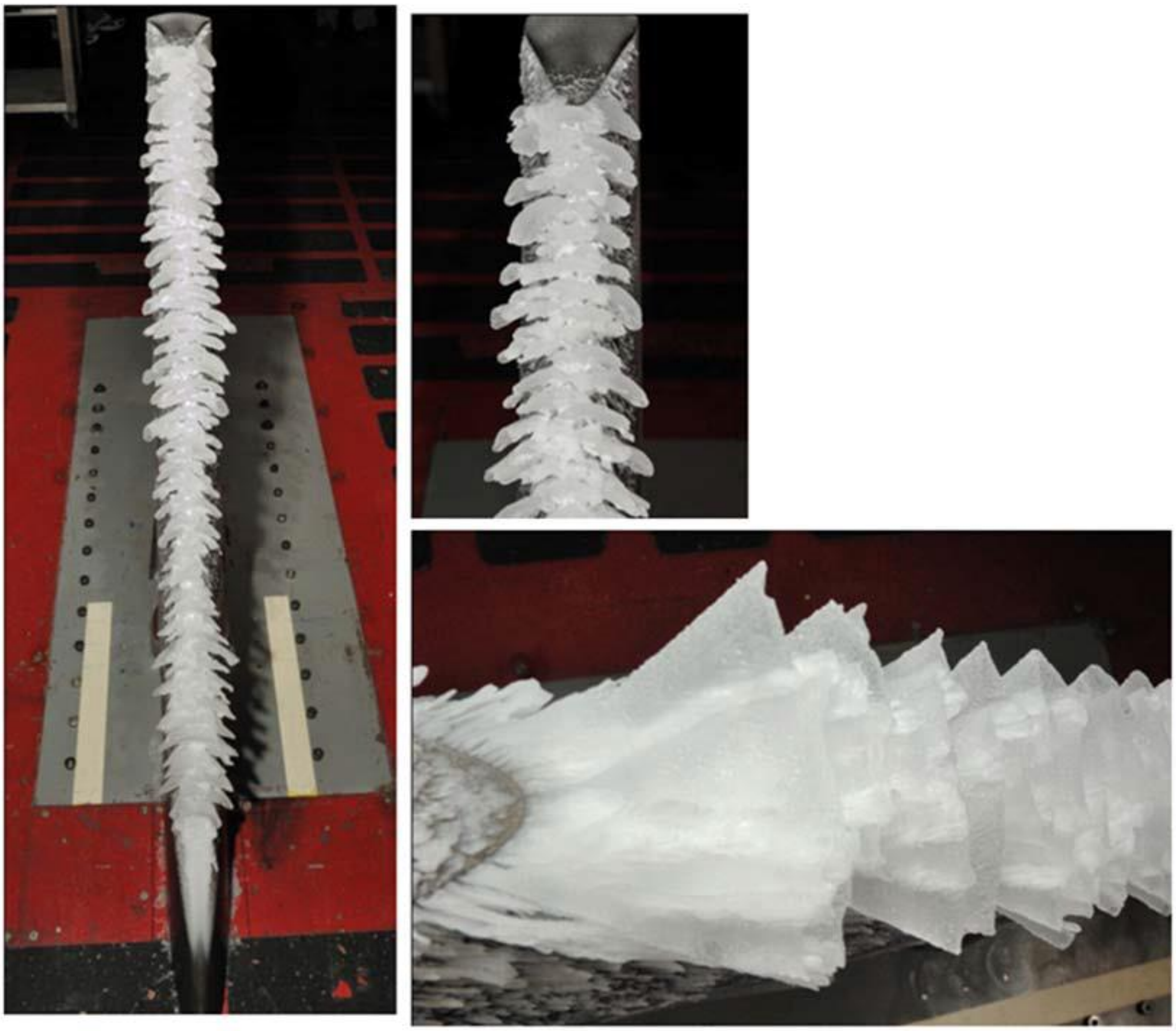

Figure 1. Photographs of a complete scallop glaze ice accreted on a 45-deg. sweep NACA 0012 airfoil in the IRT

The LEWICE3D ice accretion software was used to simulate the possible ice shapes that would be developed on the common research model wing for several different flight conditions. This was done to provide a reference for evaluation of the ice shapes that would be created on the wing section models to be tested in the IRT. Analysis was conducted to select three stations along the span of the wing, then a “hybrid” wind tunnel model was built at each of those three stations. The approach was challenged by the large size of the full-scale wing.

The full-scale wing sections of the CRM would not fit in the icing research tunnel, so a hybrid wing model design method was developed to create an airfoil with a full-scale leading edge and a truncated aft body. This method was then applied at the selected spanwise stations (20%, 64% and 83% span), as shown in Figure 2 which illustrates the hybrid wing model section compared to the full-scale section for the 64% station.

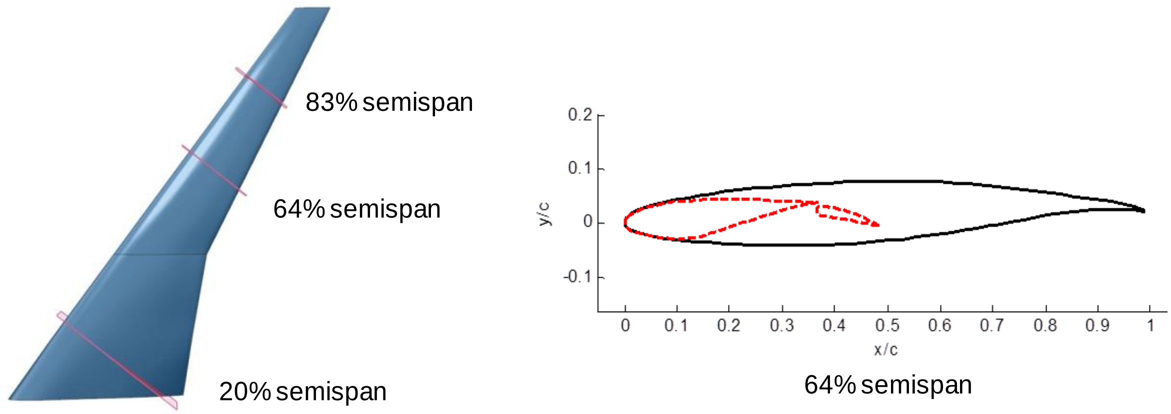

Figure 2. Design and simulation of hybrid model wing sections in 2D

Experimental ice shapes were generated on the leading edge of each model for a set of icing conditions, and then digitized with a 3D laser scanner. The ice accretion testing of the inboard, midspan and outboard models was performed in a series of campaigns in the IRT in 2015[7]. Data collected included photographs, laser-scanned ice shapes, and ice mass measurements. For aerodynamic testing with artificial ice shapes, it was necessary to develop a method to create full-span ice shapes from the ice shapes generated at the three spanwise stations[8]. The scanned ice shape data was used to develop artificial ice shapes for testing.

Then, aerodynamic testing of the wing model was conducted, both with and without the ice shapes. Wing models were built for testing at both high-Reynolds number and low-Reynolds number. The wind tunnel at Wichita State University was used for the low Reynolds number testing[9]. These data included force balance, surface pressure and wake survey measurements and surface oil and fluorescent mini-tuft flow visualization. The ONERA F1 tunnel was used for the high Reynolds number testing[10]. Both high-fidelity and low-fidelity full-span ice shapes were built for both the aerodynamic tunnels. Aerodynamic testing of the wing model with a clean leading edge and various high and low fidelity ice shapes was then conducted in both aerodynamic tunnels[11, 12, 13]. Computational simulations were done for comparable flow and icing conditions of the experiment, utilizing 3-D Reynold's Averaged Navier-Stokes (RANS) CFD for the flowfield solutions. A comparison of computational and experimental ice accretions was then made for three full-scale leading edge swept wing models spanning from floor to ceiling in the NASA Glenn Icing Research Tunnel at three difference spanwise stations.

This significant multi-year research effort resulted in a number of major results. Results showed both good ice accretion agreement and the need to further explore and better understand the complex 3D flowfield and ice accretion modeling. Hybrid wing models can be developed to enable ice accretion testing on large-scale wing leading edge geometries. A robust and efficient method has been developed to document highly detailed three-dimensional ice shape geometries. A method was created to extend the actual measured geometries to other spanwise locations across a wing model and produce realistic representations of an iced wing configuration. Scaling methods developed for straight and swept-wing geometries are critical tools to aid in test matrix development for large scale models. CFD analysis of wings and wing sections both with and without tunnel walls are critical elements to enable the design of large scale models to be tested in the IRT which will accurately represent the icing environment for such models. Computational ice accretion simulation of complete wings and associated icing tunnel wing section models is a critical element for creation of such models. Comparison of the highly complex ice shapes generated on a swept wing model to ice shapes generated in an ice accretion code, no matter how realistic such computational results might be, is a difficult activity. New methods for making such comparisons are required for assessment of the computational tools.

The comparison of CFD with experiment in this effort (at least in the first few years) indicated that there were major geometric differences between the computational and experimental ice shapes. The computational shapes predicted by the CFD approach only captured the main 2D features of the ice shapes, such as the overall contour, but was not able to predict either spanwise variations of the ice shape or small, detailed 2D features which were captured by the experiment. The three-dimensional characteristics of the experimental ice shapes could not be captured using traditional 2D tracings, but can be clearly seen in photographs and 3D scans. The main limitation uncovered was that using an essentially 2D ice accretion code had limitations when trying to simulate a highly 3D scallop shape.

Note that this case study has focused on the simulation and prediction of ice accretion on large swept wings, such as those commonly found on large commercial transports. It remains for further research to determine whether these discrepancies were great enough to produce significant differences in the aerodynamics. As such, future aerodynamic experiments are planned, or ongoing.

Of these accomplishments, many were significant collaborative efforts between experimentalists and computation. The development and validation of a 3D scanning method for digitizing complex ice shapes for swept wings was a major undertaking on its own which was necessitated by this effort. A significant amount of research effort was necessitated beforehand to develop a hybrid model to fit the large chord of the CRM in the Icing Research Tunnel.

2. Rotor Blade Icing

Well-validated, high fidelity icing tools can aid in the design, risk reduction, flight safety and certification of rotorcraft. In the area of rotorcraft icing, the interdisciplinary nature of the problem requires a particularly challenging simultaneous treatment of aerodynamics, aeroelasticity and flight dynamics. In 2008, a collaborative effort between industry, academia and government was undertaken to develop a high-fidelity suite of rotorcraft icing tools. Various methods and coupling techniques were independently developed and examined for accuracy, robustness, and efficiency as part of this effort. Several approaches for the robust coupling of a CFD, rotorcraft structural dynamics code, and an ice accretion code were successfully demonstrated[14].

In August and September of 2013, a rotor blade icing test was conducted at the NASA IRT, to further explore the physical phenomena and obtain validation data[15]. Test results addressed a number of technical challenges: rotor and fuselage ice accumulation, ice shedding from a rotating/oscillating blade, de-ice and anti-ice system performance with runback and refreeze, and shed-ice trajectories and impact. The data included: rotor ice shapes (from tracing, photograph and scanner), rotor performance (from main balance, instrumented blades), deice and anti-ice performance (temperature), and shed ice trajectories (wall panels, high speed video). Several notable firsts for the IRT were accomplished, including: first production use of the three-dimensional scanner capability, first electro-thermal deicing of a rotating scale model, first capture of a rotor shed event with a high speed camera, first supercooled large droplet ice accretion case on a rotor blade, and the first time in twenty years that a rotating model was tested in the IRT. Figure 3 shows the process of scanning the ice shape on the rotor blade.

The ice accumulation over a heated tail rotor was computed using LEWICE, then compared with to a corresponding prediction using an extended Messinger's model[16,17]. An example of this approach is shown in Figure 4. Significant differences in the computed ice shapes were seen, even though the external flow field was identical. The physical causes behind these differences were explored, with the goal to improve the prediction tools.

This effort required a collaboration between industry, academia and government to accomplish both a CFD tool and a complex ground experiment, neither of which could have been conducted by any single agency alone. In this effort, all of the participants were able to take the tool and validate it against their own in-house data.

Figure 3. Scanning the Ice on a Tail Rotor in the IRT

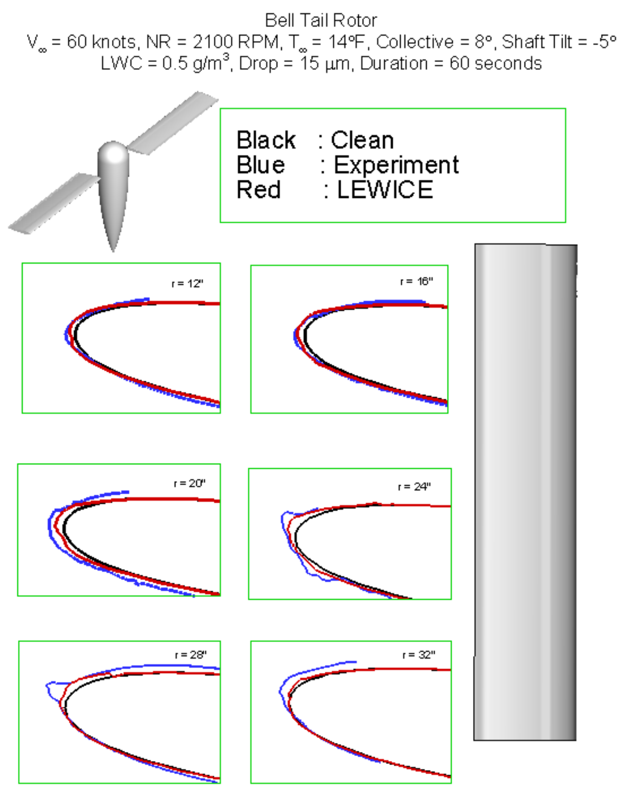

Figure 4. Comparisons of Ice Shapes Predicted vs. Experiment for Run 54 (from NASA IRT)

3. Aerodynamics of a Business Jet Airfoil with Leading Edge Ice Accretion

In the 1990's, the Icing Branch and the FAA Technical Center embarked on an effort to investigate a range of shapes and sizes of inflight ice that might accrete on the new generation of modern style airfoils. At the time, a significant database of ice shapes existed for symmetric or simple airfoil sections, for example the NACA-0012 and NACA-23012, and some previous work had also been conducted on multi-element and natural laminar flow airfoils. But there was a question as to whether or not the newer airfoil designs being developed by industry accreted ice differently. Industry was surveyed, and a number of representative airfoils were selected. The three selected airfoils were representative of a commercial transport horizontal tail-plane, a business jet main wing[18], and a general aviation aircraft main wing.

Ice shapes on the business jet airfoil were generated and recorded in the IRT, and compared with those predicted by LEWICE, the computer ice accretion code. Version 2.0 was the most recently available version at the time of this activity. Tracings were used to document the ice shapes. At the time of this study, three-dimensional ice accretions were beyond the state-of-the-art, for either CFD or experimental methods. The ice shapes were accreted over a representative subset of icing conditions encompassing the FAA's Part 25Appendix C atmospheric icing conditions.

The majority of the aerodynamic work was conducted at the NASA Langley Low Turbulence Pressure Tunnel (LTPT) facility using artificial ice shapes generated in the NASA Glenn IRT. Some aerodynamic measurements were also made in the IRT. The test matrix was designed to cover a broad range of Reynolds and Mach numbers, leaning toward the high end of velocities applicable to those of a modern business jet in typical icing conditions. Not all combinations of Mach and Reynolds numbers could be run for all ice shapes, due to limitations of test time and tunnel conditions. Testing showed that the ice caused significant degradation in airfoil performance, and were consistent with previous research.

Two of the many ice shapes obtained on the business jet model were selected as representative test cases for CFD analysis, and to examine whether any experimental benefits could be obtained by smoothing the complex ice shapes for subsequent aerodynamic testing. Smoothed, two-dimensional ice shapes were also made so that comparisons could be made between original castings and smoothed, representative test cases. In general, differences between the three-dimensional features and the smoothed ice shape were found to be small, particularly when compared to the clean airfoil. However, the importance of these differences was found to depend on the purpose of the evaluation. In some instances, the cast-versus-smooth ice shapes were more sensitive on the general aviation model than on the business jet model. The size and scope of the business jet ice shape study highlighted the importance of a realistic validation database in order to attain a certain level of acceptance of LEWICE for some certification uses, and the importance of test method development.

The computational study was also subsequently conducted to address how well CFD could predict lift, drag, surface pressure and the velocity field as a function of the angle-of-attack for a 2-D airfoil with a glaze or a rime ice shape accreted on the leading edge[19]. These were the 22.5-minute glaze shape 944, and the 16.7-minute rime shape 212. Glaze ice shapes are characterized by an ice buildup with two or more protruding horns near the airfoil's leading edge, resulting in a large region of separated flow, even at zero angle of attack. Rime ice accretion featured rough and jagged surfaces, but no protruding horns. Some of the complexity of the glaze ice shapes were found to be especially challenging to the CFD predictions. Both open source and commercially-available CFD codes were utilized for these studies.

Particular attention was paid to the effects of turbulence modeling and grid quality. An example of this is shown in Figure 5. The highly complex ice geometries required the development of new methods to generate high-quality single- and multi-block structured grids. This effort also highlighted the benefits of selecting representative, generic geometries for analysis. In this effort, all of the tool validation was overseen by a centralized team, using publicly-available information. In retrospect, some efficiencies were realized by having tool development and multi-facility experimental testing led and conducted by the same organization.

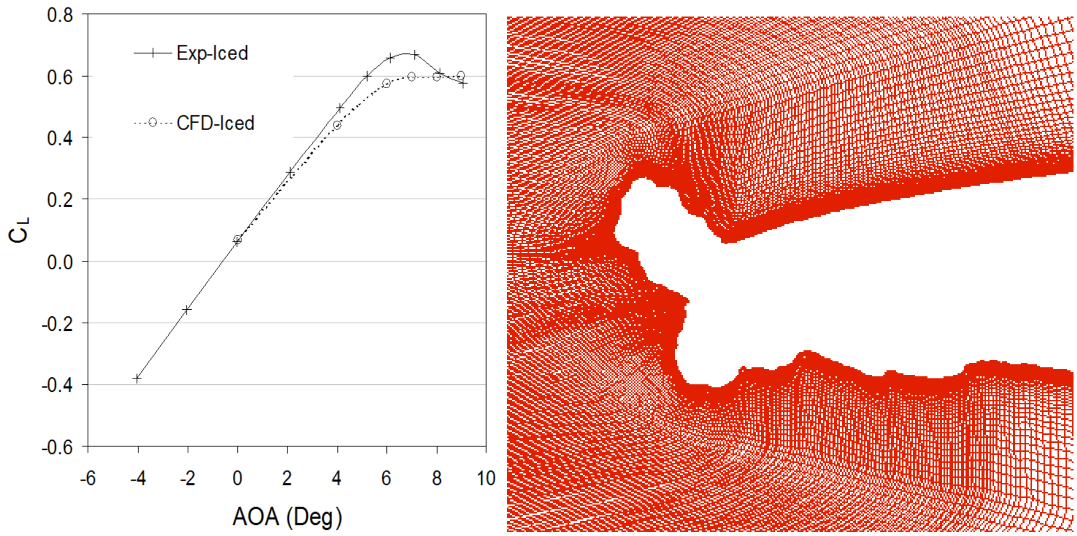

Figure 5. Lift coefficient vs. angle of attack, CFD vs. experiment (left) and grid for 944 ice shape (right), GLC-305 airfoil

IV. Conclusions

Ice accretion codes and prediction tools are constantly being stretched to new applications. This requires new CFD tool development. Validation data are also required. This requires new generic wind tunnel models which must meet geometric and condition requirements but also stay within resource restraints. The data for CFD validation also often requires new test methods, which cannot be designed without CFD. Sometimes, a first principles tool can simulate things which are difficult to replicate experimentally.

Some additional questions remain unanswered. What if there is no facility available to test the conditions, and they are rare in nature? Another concern is relative to new regulations, new vehicles or new operational concepts. How do we go about the validation of future three-dimensional, unsteady problems, since two-dimensional methods are no longer sufficient for geometric validation? Since the advent of digital scanning techniques has brought on a step-change in the fidelity of ice shape measurements, how good is good enough when it comes to accuracy?

There remain other phenomena in aircraft icing which will almost certainly spur future research. The development and validation of tools for novel ice protection systems, the prediction and modelling of ice shedding, and the quantitative measurement of ice adhesion on advanced materials are just a few examples of the ongoing need for collaboration between the experimental and computational disciplines.

Acknowledgments

The authors would like to acknowledge Gene Addy, Gustavo Fujiwara, Stephanie Camello, Christoper Lum, Mark Potapczuk, Mike Bragg, Lakshmi Sankar, Robert Narducci, Robert Kunz, Jason Wright and Roger Aubert. In addition, none of this would have been possible without the dedication and professionalism of the technicians and engineers of the Icing Research Tunnel.

References

[1] 14 CFR, Aeronautics and Space, Part 25 Airworthiness Standards: Transport Category Airplanes, Section C25.1: Appendix C;" published by the Office of the Federal Register, National Archives and Records Administration, Washington, DC., Amdt. 25-140, effective 5-Jan-2015.

[2] Slotnick, J., Khodadoust, A., Alonso, J., Darmofal, D., Gropp, W., Lurie, E., and Mavriplis, D., "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA CR-2014-218178, March, 2014.

[3] Wright, W., and Porter, C., "A Revised Validation Process for Ice Accretion Codes," AIAA Paper 2017-3415, presented at the 9th AIAA Atmospheric and Space Environments Conference, Denver, CO, 5-9 June, 2017.

[4] Levinson, L., and Wright, W., "IceVal DatAssistant- An Interactive, Automated Icing Data Management System," presented at the 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 7-10 January, 2008.

[5] Broeren, A., Potapczuk, M., Riley, J., Villedieu, P., Moens, F., and Bragg, M., "Swept-Wing Ice Accretion Characterization and Aerodynamics, AIAA Paper 2013-2824, presented at the 5th AIAA Atmospheric and Space Environments Conference, San Diego, CA, 24-27 June, 2013.

[6] Fujiwara, G., Bragg, M., Camello, S., and Lum, C., "Computational and Experimental Ice Accretions of Large Swept Wings in the Icing Research Tunnel, AIAA Paper 2016-3734, presented at the 8th Atmospheric and Space Environments Conference, Washington, D.C., 13-17 June, 2016.

[7] Broeren, A.P., Potapczuk, M.G., Lee, S., Malone, A.M., Paul, B.P., Jr., and Woodard, B.S., "Ice-Accretion Test Results for Three Large-Scale Swept-Wing Models in the NASA Icing Research Tunnel," AIAA Paper 2016-3733, June 2016; also NASA/TM—2016-219137, Sept. 2016.

[8] Camello, S.C., Lee, S., Lum, C.W., and Bragg, M.B., "Generation of Fullspan Leading-Edge 3D Ice Shapes for Swept-Wing Aerodynamic Testing," AIAA Paper 2016-3737, June 2016.

[9] Woodard, B.S., Broeren, A.P., Diebold, J.M., and Bragg, M.B., "Preliminary Testing of Low Reynolds Number Aerodynamics for a Swept Wing with Artificial Ice Roughness," DOT/FAA/TC-17/48, Sept. 2017.

[10] Broeren, A.P., Lee, S., Woodard, B.S., Lum, C.W., and Smith, T.G., "Independent Effects of Reynolds and Mach Numbers on the Aerodynamics of an Iced Swept Wing," AIAA 10th Atmospheric and Space Environments Conference, Atlanta, GA, June 25-29, 2018 (submitted for publication), 2018.

[11] Camello, S.C., Bragg, M.B., Broeren, A.P., Lum, C.W., Woodard, B.S., and Lee, S., "Effect of Ice-Shape Fidelity on Swept-Wing Aerodynamic Performance," AIAA Paper 2017-4373, June 2017.

[12] Lee, S., Broeren, A.P, Woodard, B.S., Lum, C.W., and Smith, T.S., "Comparison of Iced Aerodynamic Measurements on Swept Wing from Two Wind Tunnels," AIAA 10th Atmospheric and Space Environments Conference, Atlanta, GA, June 25-29, 2018 (submitted for publication), 2018.

[13] Woodard, B.S., Broeren, A.P., Lee, S., Lum, C.W., and Bragg, M.B., "Summary of Ice Shape Geometric Fidelity Studies on an Iced Swept Wing," AIAA 10th Atmospheric and Space Environments Conference, Atlanta, GA, June 25-29, 2018 (submitted for publication), 2018.

[14] Kreeger, R., Sankar, L., Narducci, R., and Kunz, R., "Progress in Rotorcraft Icing Computational Tool Development," SAE Technical Paper 2015-01-2088

[15] Wright, J., and Aubert, R., "Icing Wind Tunnel Test of a Full Scale Heated Tail Rotor Model," presented at the AHS 70th Annual Forum, Montreal, Canada, 20-22 May, 2014.

[16] Kim, J., Sankar, L., Palacios, J., and Kreeger, R., "Numerical and Experimental Study of Rotorcraft Icing Phenomena," presented at the 41st European Rotorcraft Forum, Munich, Germany, 1-4 September, 2015

[17] Sankar, L., Kunz, R., Kreeger, R., et. al., "Numerical Simulation of Airfoil Ice Accretion Phenomena," presented at the 2nd AHS Asian/Australian Rotorcraft Forum, Tianjin, China, 8-11 September, 2013

[18] Addy, H., Broeren, A., Zoeckler, J., and Lee, S., "A Wind Tunnel Study of Icing Effects on a Business Jet Airfoil," presented at the 41st AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 6-9 January, 2003.

[19] Chi, X., Zhu, B., Shih, T., Addy, H., and Choo, Y., "CFD Analysis of the Aerodynamics of a Business Jet Airfoil with Leading Edge Ice Accretion," AIAA Paper 2004-0560, presented at the 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 5-8 January, 2004.