THE EXPERIMENTAL INVESTIGATION OF A ROTOR HOVER Icing MODEL WITH SHEDDING

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ABSTRACT

Icing environments have long been an issue for rotorcraft. Flight in icing conditions is fraught with operational hazards, including reduced vehicle performance and large torque rises. Shedding of ice from blades due to centrifugal forces poses a ballistics danger to the aircraft and creates large vibrations due to imbalanced rotors. Modeling the effects of accreted ice on rotorcraft flight performance has been a challenge due to the complexities of periodically changing conditions as well as spanwise variations of angle of attack, velocities and surface temperatures. A new icing model has been developed to model the ice accretions across a rotor in hover. A shedding module is used to predict the shedding events and station. This model was correlated with published ice shapes for both small and full scale ice accretion results. The shedding module was evaluated based upon experimental results in the newly developed Adverse Environment Rotor Test Stand (AERTS). Favorable comparisons have been made between ice thickness, impingement limits and ice shape, especially at inboard stations. Shedding behavior was also evaluated, but required correction factors to improve test data correlation. Further investigations are required, but the icing model has demonstrated the ability to predict rotor icing trends.

INTRODUCTION

A critical operational problem for rotorcraft is flight in icing conditions. Ice accretes on critical components of rotorcraft, such as rotor blades, engine inlets, windscreens, and empennage surfaces, when combinations of temperatures close to freezing and high supercooled water concentrations are encountered (Ref. 1). Accreted ice can severely reduce aircraft performance, rendering safe flight impossible. The effects of a highly modified flowfield resulting from accreted ice include slightly reduced sectional lift coefficient and modified pitching moment characteristics, as described in References (2) - (4). The most significant effect of icing, however, is the increase in blade profile drag (Ref. 5). Ice does not typically accrete in a uniform coating on the rotor; rather a rough and sometimes jagged structure is formed at the leading edge, causing premature flow separation and a considerable reduction in rotor lift/drag ratio. The torque can increase rapidly as described in Reference (6), potentially reaching the transmission or engine limits (Ref. 1). This trend has been observed both in flight and in experiments in icing wind tunnels (Ref 7, 8).

Another problem of rotorcraft icing is the due to the high rotational speed of the rotor. The system generates high centrifugal forces on accreted ice, especially near the tips. This provides a natural de-icing capability, which is theoretically beneficial for helicopter. The problem arises when the ice does not shed in a symmetric fashion from all blades. Uneven ice accretion causes rotor imbalance and subsequent severe vibrations. The transmission or engine torque limits can be exceeded due to the fluctuating drag, making maintaining a given flying condition impossible for the pilot (Ref. 1). Furthermore, researchers have identified problems with damage to the fuselage, engines, empennage and tail rotors from high velocity shed particles. Larger, multiengine vehicles,
either by significant code complexity or more importantly by a lack of available validation data. The lack of data may be a result of the existence of few icing facilities focusing on rotorcraft research. With the closing of the Canadian National Research Council (NRC) Helicopter Spray Rig, only two primary facilities remain. Ice protection system and other component level testing can be accomplished at a number of icing wind tunnels, but these tests are often limited by tunnel velocity and the fact that the centrifugal forces inherent to rotor rotation are not represented. Complete rotor icing studies can be undertaken in NASA Glenn’s Icing Research Tunnel (IRT), but model rotor diameters are limited to 6 ft by the test section (Ref. 13). Full scale studies may be accomplished with the Helicopter In-flight Spray System (HISS), but detailed icing shapes are difficult to acquire. Test aircraft need to descend through layers of warm air and may shed ice prior to landing. This often causes ice shedding, which aside from being inherently dangerous, eliminates the possibility of ice shape data collection.

**RESEARCH OBJECTIVE**

The primary objective of this research was to develop a rotorcraft icing model that includes the effects of shedding for the ultimate application to ice protection system sizing studies. The second objective was to validate the model based upon published icing results, including both full and small scale. Finally, the third objective was to correlate the icing model accretions and shedding behavior to experiments performed in a new icing facility. The current research is the first attempt to correlate predicted and experimental ice shapes in the new facility.

**ARISP MODEL**

The Vertical Lift Research Center of Excellence at the Pennsylvania State University has developed a new icing facility for rotorcraft icing research. Achieving an initial operational capability in November 2009, the Adverse Environment Rotor Test Stand (AERTS) is designed to generate an accurate icing cloud around test rotor. The primary mission of the facility is to evaluate new ice protection system concepts and test new “ice phobic” materials. Efforts are currently underway to fully calibrate the lab for ice accretion model validation.

The AERTS Facility required an ice accretion model to assist in calibration of the icing cloud. The primary objective of the model is to support basic rotor icing research. If the model can accurately predict impingement limits and shedding location and frequency, it will be useful for ice protection system sizing studies by identifying the required location and relative power density of such systems. As both the facility and model grew in complexity, it became the AERTS Rotor Icing, Shedding and Performance Model (ARISP). In addition to calculating ice accretion on a test rotor, the model accounts for ice shedding and torque rises. The AERTS specific corrections in the code can be disabled and the model can be used as a simple supplement to more
complex icing codes such as those currently under development under the current “High Resolution CFD Analysis of Rotorcraft Rotor Icing” NRA program. These models require a full flow field solution and rotor dynamics analysis as well as an ice accretion calculation.

The model is based around NASA’s LEWIs ICE Accretion program (LEWICE). This industry standard program has been extensively validated in the Icing Research Tunnel (IRT) at NASA Glenn Research Center and is described in Reference (14). The overall process is similar to the model developed by Britton (Ref. 15), but performance degradation is modeled empirically using coefficients derived by Flemming after extensive wind tunnel analyses (Ref. 16).

Like most rotorcraft icing models, the ARISP code differs from a standard fixed wing icing analyses in the fact that conditions are changing as time passes. Sectional angles of attack may change due to ice accretion and/or ice may shed from the rotor. Spanwise variations kinetic heating, numbers of particles encountered and centrifugal loads are also present. As such, the icing analysis must be broken up into a number of steps, with the ice profile and performance constantly being updated. A sectional approach is taken, with rotor performance and ice accretions calculated at various rotor stations. Rotor performance is determined with a Blade Element Momentum Theory (BEMT) routine, chosen for its speed of calculation and ease of integration with LEWICE. Calculating sectional $C_l$, $C_d$, and $C_m$ and ice accretion at the same stations simplifies iced performance degradation computations. These coefficients derived from the work of Hassan (17) for the NACA 0015 airfoil. Variations in icing cloud parameters can also be easily studied with the sectional approach if required.

Corrections are made for the unique aerodynamic environment of the test chamber arising from its relatively small size based upon the work of Rossow described in Reference (18) and the results of CFD analysis presented later in the paper. These corrections, however, are relatively insignificant because test rotors are operated at low thrust levels. These corrections are disabled for model correlations to rotors in free flight.

Based upon the BEMT module and icing conditions, inputs are generated for LEWICE and LEWICE is run. Icing results are then read and a post processors assesses shedding criteria and updates the sectional airfoil performance. A schematic of this process is shown in Figure 1, which loops until the final icing time is achieved. Figure 2 highlights the stepwise process that is used for the analysis. The duration of each icing step can be user selected or based upon the LEWICE automatic time stepping selection process.

![Figure 1: ARISP Overview](image1)

As the model was developed, individual modules were validated. Some test results of this process are shown in the following figures. The ARISP BEMT module is compared to the NASA Small Scale rotor, described in Reference (19), in Figure 3. This reference was chosen because the size of the rotor was similar to that used in the AERTS facility. The ARISP model slightly over predicts the rotor performance polar, which is expected because three-dimensional effects are neglected.

![Figure 2: ARISP Icing Concept](image2)
A similar validation effort was undertaken for the stepwise icing analysis procedure utilized by the ARISP. The first icing model validation step was evaluating the accuracy of cross sectional ice shapes to published literature. ARISP analytical results were compared to experiments undertaken in the IRT in 1988. The test rotor and accreted ice shapes are described in Reference (13). Since the tests were accomplished with the model rotor in forward flight, the collective pitch is trimmed to such that the ARISP model hover sectional angles of attack match the experiment. This value was around 13˚ and was recomputed for each test case. As shown in Figure 4 and Figure 5, the process yields accurate results for the accreted ice shape for the inboard regions of the rotor.

Additional correlations were conducted with flight icing flight trial data. The ARISP model was compared with results from Flight E of the Helicopter Icing Flight Test (HIFT) program, conducted with a UH-1H aircraft at the NRC Helicopter Spray Rig. This test program is described in Reference (20) and contains results of ice accretions in hover for a full-scale aircraft. The ambient temperature was corrected from -19˚C to -14˚C per Reference (12) and the results are shown in Figure 6.

As with the scale rotor correlations, the ARISP model provides relatively accurate results for the inboard regions of the rotor. The reason for ice over prediction at the tip is currently unknown, but may be related to droplet bounce, centrifugal effects and a non-uniform LWC as described in Reference (12). Also, the flow velocity is higher than the maximum LEWICE validation envelope of 475 ft/sec contained in Reference (21). Application of LEWICE beyond this velocity is possible, but care must be used, as issues with the potential flow solver and heat transfer may be encountered.
Further investigations of the model focused on the tip region of the blade. Predictions of ice extent were determined based upon Reference (16) and are shown in Figure 7. Ice extent indicates the station inboard of which ice is expected to accrete. The total temperature rise is calculated across the blade span are calculated Limits for an AERTS test rotor were calculated with the ARISP model are plotted against the predication. Trends agree relatively well, with the ARISP model predicting ice extent by approximately 30%. This was expected based upon ice shape correlations. Multiple droplet sizes are added to the chart to investigate their effect on ice extent. As expected, all droplets followed the same trend, regardless of size since the prediction method is only based upon static temperature, station Mach number, thermodynamic recovery factor and LWC.

Limits on ice shape correlations are not seen as major restrictions for the icing code. Since the AERTS Facility is primarily intended to evaluate for ice protection systems, the location of ice is more important than the exact ice shape. Accurate impingement limits help size ice protection systems, so if the ARISP model can predict them, it can be applied to design trade studies.

**SHEDDING IMPLEMENTATION**

The ARISP Model incorporates ice shedding due to centrifugal forces inherent to rotating systems. As with the ice accretion and performance modeling, a quasi two dimensional approach is taken, with analysis starting at the rotor tip, where high centrifugal forces are found.

The analysis procedure is similar to that developed by Fortin (Ref. 6), but the ice geometry is computed with LEWICE instead of with empirical formulas. Analysis starts at the rotor tip and propagates inboard as described by Figure 8. Each ice element is subjected to the forces shown in Figure 9. The net aerodynamic force is considered to be negligible for the low tip speeds in the current research per the analysis of Scavuzzo in Reference (22).
Ice is assumed to shed if centrifugal force exceeds both the adhesion and cohesion (tensile) forces, defined by the following equations:

\[ F_{\text{centrifugal}} = \left( \rho_{\text{ice}} V_{\text{ice}} \right) r_{\text{element}} \Omega^2 \]  
\[ V_{\text{ice}} = A_{\text{ice}} dx \]  
\[ s_{\text{contact}} = s_{hi} + s_{low} \]  
\[ F_{\text{adhesion}} = \tau s_{\text{contact}} dr \]  
\[ F_{\text{cohesion}} = \sigma A_{\text{ice}} \]

where:
- \( \rho_{\text{ice}} \) = ice density
- \( V_{\text{ice}} \) = ice volume
- \( r \) = radial position
- \( dx \) = differential ice element length
- \( s_{hi}, s_{low} \) = ice impingement limits

The ice cross sectional area and ice adhesion areas are calculated with LEWICE and are updated for each icing analysis step. The Jones model, detailed in Reference (23), is used to evaluate the ice density as a function of test condition.

Cohesive (tensile) ice strength is taken from Reference (24). Currently, ice shear adhesion strength values are taken from literature as well. The problem, however, is that the published data varies significantly for a particular material as shown in Table 1.

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<tr>
<th>Author/Date/Reference</th>
<th>Aluminum Shear Adhesion Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loughborough* 1946 (25)</td>
<td>81 ( \text{psi} ) ( \approx ) 558 ( \text{kPa} )</td>
</tr>
<tr>
<td>Stallabrass and Price† 1962 (26)</td>
<td>14 ( \text{psi} ) ( \approx ) 97 ( \text{kPa} )</td>
</tr>
<tr>
<td>Itagaki† 1983</td>
<td>4 - 23 ( \text{psi} ) ( \approx ) 27 - 157 ( \text{kPa} )</td>
</tr>
<tr>
<td>Scavuzzo and Chu† 1987 (27)</td>
<td>13 - 42 ( \text{psi} ) ( \approx ) 90 - 290 ( \text{kPa} )</td>
</tr>
<tr>
<td>Reich* 1994 (28)</td>
<td>130 ( \text{psi} ) ( \approx ) 896 ( \text{kPa} )</td>
</tr>
<tr>
<td>PSU AERTS Pull Test*</td>
<td>76 ( \text{psi} ) ( \approx ) 526 ( \text{kPa} )</td>
</tr>
</tbody>
</table>

*Freezer Ice, †Impact Ice

There are few reasons for the variation. Differences are generated in test results based upon the manner in which ice was accreted on the test material. Some authors have used “freezer” ice, in which liquid water is allowed to slowly freeze to the test material. This does not properly represent encounters with natural icing clouds which involves supercooled water droplets impacting an exposed surface. Other authors have studied accreted or impact ice to include the differences in ice structure relative to the freezer ice. The complete parameters of the test cloud are not always detailed, however.

A related problem is that not all parameters of a particular material are reported. For example, aluminum has many grades and finishes, each with a slight difference in surface structure. This has an effect on surface roughness, which has been shown by Chu and Scavuzzo to have an effect on shear adhesion strength (27). Surface roughness issues are particularly important for rotorcraft, which may operate in both erosive sand/rain environments and icing conditions. An eroded blade leading edge will have an effect on the shedding performance of the rotor.

Another cause of discrepancies is differences in test method and facilities. Various mechanical methods have been used and each test mechanism has inherent differences. In addition, icing facilities have different limitations, and some require that data ice is accreted in one location and then the ice and fixture are moved to another location for testing. Moving the ice introduces mechanical and thermal shocks that influence data accuracy. This effect has been seen in previous testing in the AERTS Facility. The velocity limitations of most icing
wind tunnels is the most important issue when applying the data to rotorcraft icing analyses.

**AERTS FACILITY DESCRIPTION**

The test facility, shown in Figure 11, is based around a 120 HP (89 kW) motor capable of driving a 9’ (2.75 meter) diameter rotor system. A robust rotor hub from a QH-50D DASH UAV provides the ability of safely testing a variety of experimental rotors. A six-axis load cell, accelerometers and shaft torque sensor provide rotor performance data.

The rotor system is mounted inside of a 20’ x 20’ x 20’ (6.1 x 6.1 x 6.1 meter) industrial freezer capable of maintaining a temperature of -22˚F (-30˚C). A slip ring assembly with 24 signal channels and 24 high power channels provides the ability to monitor various on-blade systems and power ice protection systems.

The primary feature of AERTS facility is the icing system. It features 15 NASA Standard Icing Nozzles arranged in two concentric rings in the ceiling of the test chamber as shown in Figure 12. The inner ring has a diameter of 40” (1.0 m) and the outer ring has a diameter of 84” (1.3 m). These nozzles are provided with precise amounts of air and reverse-osmosis filtered water to generate droplet Mean Volumetric Diameters (MVD) between 10 and 50 µm.

The AERTS facility has a variety of challenges owing to the unique aerodynamic environment of the small test chamber. The test chamber ballistic wall was offset from the freezer walls to allow flow to circulate behind them. Gaps at the floor and ceiling allow for recirculation.

Computational Fluid Dynamics (CFD) has been used to analyze the laboratory for the current test rotor configuration. For these studies, only performance trends were sought, so the Solidworks Flow Simulation CFD package was used. This software uses a Farve-Averaged Navier Stokes solver with a κ-ε turbulence model. The rotor geometry is specified inside of a rotating fluid subdomain. The solution is solved iteratively with relaxation to properly resolve flow at the rotating/non-rotating boundaries. Details of the solver and validations examples are contained in Reference (29). The icing nozzle input velocities are modeled based upon bench top experiments conducted in the laboratory.

Ideally, a maximum rotor diameter would be 2.5 feet (0.7 m) to achieve a ground clearance of at least 2 rotor diameters, required to ensure performance measurements are free from ground effects (Ref. 30). This small diameter is precluded by the size of the rotor hub and by the desire to have a large enough blade to accurately measure ice shapes and establish icing trends. The recirculation patterns are shown in Figure 14 for a 9 ft (2.75 m) diameter, 6.8 inch (15.2 cm) chord, NACA 0015 rotor at 600 rpm, and 5˚ of collective pitch. This is a standard
operation point for the AERTS chamber, with a $C_T = 0.0005$. Two separate circulation patterns are created. The first is flow through the rotor and around the ballistic walls, while the second, stronger circulation is generated inside of the ballistic walls as shown in Figure 14.

![Figure 14: CFD Model Cross Section of AERTS, showing recirculation around the ballistic wall and rotor support structure with flow tubes](image)

The stronger circulation is generated by a combination of rotor tip vortices and nozzle placement. Velocities of up to 110 ft/sec (11 m/s) can be generated 2” downstream of the nozzles at higher pressure settings. Figure 15 shows this effect on the induced velocity through the rotor. The octagonal ballistic wall is clearly visible. The nozzle effect on the development of the tip vortices is indicated by Figure 16.

![Figure 15: CFD Model Cross Section of AERTS, showing velocity contours in a plane directly above the rotor plane](image)

Since rotor performance studies are undertaken in the AERTS facility, the primary interest in the CFD studies was the effect on the icing cloud. In most icing facilities, such as icing tunnels, supercooled particles pass through the test section and are removed from the test environment if they do not accrete on the model. In the AERTS facility, particles are not removed, and instead circulate around the test chamber. This has implications for the icing cloud, as the supercooled particles may freeze-out into ice crystals creating a non-uniform icing cloud. The crystals could then erode ice shapes, negatively affecting attempts at accretion model validation.

Particle trajectories were plotted for various rotor conditions to understand how the particles are distributed in the chamber. This influences nozzle placement, which is important because the small size of the test chamber places them only 4 feet (1.2 m) above the rotor. Particles were injected into the model at the nozzle locations as shown in Figure 17.

![Figure 16: CFD Model Cross Section of AERTS, showing velocity contours around the ballistic wall and rotor support structure (shaded in red)](image)

![Figure 17: CFD Model Cross Section of AERTS, showing 20 µm particle distribution in the chamber around the ballistic wall and rotor support structure (shaded in red)](image)
As expected, the small supercooled droplets follow streamlines due to their low inertia. Some particles travel behind the ballistic wall, but most circulate around the blade tips. This generates a spanwise distribution of LWC, with higher concentrations at the rotor tip. The distribution differs for each nozzle configuration and must be experimentally determined. The particles have approximately 0.15 seconds between exiting the nozzles and crossing the rotor plane to supercool, similar to the IRT.

**AERTS FACILITY VALIDATION OVERVIEW**

The ARISP analytical model was applied to the AERTS chamber to evaluate its ability to predict ice shapes and shedding. The test rotor was based on shortened Schweizer 269 main rotor blades. The blades were selected because they feature a NACA0015 airfoil and an aluminum outer skin. The generic airfoil is beneficial because it has icing data available for correlation purposes. The aluminum surface is important because shear adhesion strength data exists for the material, so shedding predictions could be tested. Specialized blade grip adapters mount the 6.8” (17.2 cm) chord blades to the QH-50 rotorhead to form a 7.75’ (2.36 m) diameter rotor. The blades have a -2.13˚ twist. Structural and dynamics analyses were completed on the blades and grip adapters to ensure test safety. Painted stripes on the aft portions of the blades identify stations for consistent ice thickness and tracing measurements. All paint and coatings were removed from the leading edge via bead blasting so that ice accretes to the bare aluminum. The surface was not polished afterwards to simulate an in-service condition.

Prior to each test, the chamber temperature was stabilized at the appropriate temperature and the rotor spooled up to the desired RPM. The icing system was then activated and the rotor was exposed to the icing cloud for a precise amount of time. Other than temperature, icing conditions are not explicitly measured in the AERTS chamber, however. Temperature was recorded at multiple locations with thermocouples and was maintained within ± 1 °C.

Droplet size is controlled with precise inputs of water and air to the nozzles. Feedback control loops maintain these pressures within 1 psi and are monitored during the test. These pressures were converted to droplet size via the NASA Glenn Research Center calibration tables, giving an input droplet size of ± 2 µm. Once the droplets are inducted into the chamber, there is no attempt to monitor them as the AERTS has no dedicated sensor.

As with the MVD, there is no direct measurement of LWC inside of the chamber. Most LWC sensors require a minimum velocity over them to properly characterize the icing cloud. Also, the sensor determines the LWC at a single point in the chamber, which does not provide enough information to characterize the unique testing environment. These two issues led to the development of a process to calculate the LWC experimentally based upon icing wind tunnel calibration procedures. At the conclusion of each test, the accreted ice thickness is measured at 11 blade stations. This thickness is converted to LWC via Equation 6, contained in the IRT calibration process detailed in Reference (31).

$$LWC = \frac{4.34 \times 10^4 \times \text{ice thickness}}{n \times E \times V \times \text{time}}$$

where:

- ice thickness = measured
- n = freezing fraction
- E = station catch efficiency
- time = icing time (seconds)
- V = station velocity (kts)

The Messinger model is used to compute the freezing fraction via the process described by Anderson and Tsao in Reference (32). Since the freezing fraction is a function of LWC, a computer code iterates on the parameters to determine the test LWC. The calculation process has been validated against the test cases reported in Reference (32). The process is sensitive, as small errors in the measurement of final ice thickness can generate large errors in the LWC calculation. Due to this issue, and the lack of direct particle size measurement the calculation of LWC is estimated to be ± 25 % for the current research.

**AERTS VALIDATION TEST POINTS**

A total of 34 cases were run in the facility. The first 21 cases were considered shakedown tests, which explored the limitations of the icing system and establish facility best practices. These tests highlighted issues with generating clouds with LWCs below 3.0 gr/m³, the upper icing severity established by FAR Part 29 Appendix C. The high LWC produced significant issues with ice crystals, as ice shapes were highly eroded and did not match LEWICE predictions. The final ice shapes, regardless of icing condition were reduced to pointy ice spears, as shown in Figure 18. These spears are not representative of expected ice accretions, especially at warm temperatures (> - 5°C) and larger particle sizes (> 25 µm).
After experimentation, using only five nozzles in the outer ring (see Figure 12) was found to generate an icing cloud with proper droplet density and with reduced ice crystals. In addition, screens were added beneath the rotor plane to catch droplets before they crystallized and recirculated. The screen are constructed from 0.25” x 0.25” (0.64 cm x 0.64 cm) mesh and are mounted approximately 36” (0.9 m) below the rotor. Heaters were added to the screens to keep them from clogging by melting the accreted ice and they are cleaned between each test. If nozzle settings are properly selected, the screens do not collect large any significant ice and remain clean.

Other tests investigated the effects of collective pitch. Increasing pitch increased cloud mixing, but greatly influenced the tip ice accretions. Figure 19 shows the dropoff in ice thickness as with a small increase with collective pitch. Running the rotor at 0˚ collective was considered, but due to blade twist and the nature of the test facility, it was desired to have a slight induced velocity through the rotor to draw the supercooled water droplets through the plane of the rotor. This is especially important at low nozzle pressure settings, where the output velocity significantly decreases.

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*Icing system settings issues prevented the icing cloud from being accurately characterized*
The low tip speed is not directly applicable to rotorcraft, but centrifugal force similar to a full scale vehicle. For a given ice accretion shape, the centrifugal acceleration on the ice at 0.8r of the AERTS test rotor was equal to that of a CH-47 rotor at 0.7r. This is important when investigating ice shedding.

The test points spanned a large portion of the AERTS operational envelope. Most points were close FAR Part 25/29 Appendix C icing envelope, but due to issues controlling the LWC inside of the test chamber, some lie significantly outside. The most important issue with test points was the relationship between the LWC and MVD. For the test points near −10°C, the relationship between the established icing envelope is shown in Figure 21. As experience with the icing system increases, settings to generate the desired cloud will be better understood.

**AERTS TEST RESULTS**

Post test documentation included photographs, ice thickness measurements and ice tracings. Typical ice accretions are provided in Figures 22 through 24. After each test, the ice accretions were completely removed, returning the rotor to a clean condition.
The accreted ice stagnation thickness was measured at 11 radial positions calipers. The calipers were cooled in the freezer for at least 5 minutes to prevent them from melting the ice shapes. Trends are shown in Figure 25. The cases with the highest thicknesses were difficult to measure due to the ice horns, so they are non-linear near the tips. If large horns were encountered, the stagnation thickness was recorded by examining ice tracings. If large horns were encountered, the stagnation thickness was recorded by examining ice tracings.

The thicknesses were then converted to LWC using the process described previously. Most cases exhibited a radial increase in LWC, which was expected due to nozzle placement and droplet recirculation in the tip vortex structure. Once the LWC was calculated, the ARISP model was run for the particular test case with the appropriate inputs. The experimental stagnation thicknesses and accreted ice shapes were compared to the model. The relative error between experimental and predicted thicknesses is shown in Figure 27 for selected blade stations.

The thickness correlations do not provide enough information because shape is not considered. Accretions may have the same stagnation thickness, but have significantly different shapes. Figure 28 is an example of this. The shape is ultimately more important, as it is responsible for performance degradation. Large glaze ice horns generate larger increases in sectional airfoil drag coefficients than the more aerodynamic rime spears. In order to make shape comparisons, tracings taken for each case at 0.7r, 0.8r and 0.9r and compared to the ARISP model. Tracings were not taken at inner blade stations because the cloud density dropped off inboard of 0.6r. In order to quantify the shapes, two parameters were considered between the experimental and predicted ice
shapes. First, the difference in impingement limits was quantified. Figure 29 displays the relative error between the impingement limits prediction and experiment. Due to the nozzle location above the rotor plane, the impingement limits were difficult to measure after a test. Since the icing cloud is not instantly removed from the test chamber, additional accretions are made during rotor spool down. As the cloud settles in the room, additional particles settle to the upper surface of the blade. These accretions are not included in the impingement limit calculations.

Qualitative comparisons were made between the shapes. A three-tiered system was used, with the following figures providing examples from each class. The primary criteria for the evaluation included impingement limits, thickness and ice cross sectional area. Very good correlations were given a green rating. Fair correlations were assigned a yellow rating, while poor correlations were labeled with a red rating.

The results from this comparison are given in Table 3. As it can be seen, most of the ice shapes were generally close to the predications. Errors arise from the fact that the MVD and LWC parameters of the icing cloud are not directly measured. The accretions provide accurate enough ice shapes for the evaluation of ice protection systems and evaluation of ice accretion protective materials.

<table>
<thead>
<tr>
<th>Case</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7r</td>
<td>0.8r</td>
</tr>
<tr>
<td>24</td>
<td>Y</td>
</tr>
<tr>
<td>25</td>
<td>Y</td>
</tr>
<tr>
<td>26</td>
<td>Y</td>
</tr>
<tr>
<td>27</td>
<td>Y</td>
</tr>
<tr>
<td>28</td>
<td>R</td>
</tr>
<tr>
<td>29</td>
<td>Y</td>
</tr>
<tr>
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<td>G</td>
</tr>
<tr>
<td>32</td>
<td>G</td>
</tr>
<tr>
<td>33</td>
<td>R</td>
</tr>
<tr>
<td>34</td>
<td>Y</td>
</tr>
</tbody>
</table>
Only one case presented significant variation with respect to ice shape predicting. Case 28 tested large particles at cold temperatures, well outside of the FAR Part 25/29 Appendix C envelope.

**SHEDDING CORRELATIONS**

Shedding characteristics of the NACA 0015 blade testing in the AERTS facility were investigated to determine suitability of the model in predicting such events. Most icing experiments presented in the prior section were run for three minutes for comparison purposes. For shedding event investigation cases were run until shedding occurred. Due to temperature control limitations in the test chamber, all cases were undertaken at warmer temperatures to improve test results. When shedding was detected with the load cell, the rotor was immediately shut down due to large 1/rev imbalances. A clearly audible bang from the ice impacting the ballistic wall was also an indicator of shedding. In each case, ice shed only from one blade, which was ideal for validation purposes because the second blade retained a record of the accreted ice.

As expected, ice accreted with larger particle sizes and warmer temperatures shed before cases with smaller particles and colder temperatures. This is due to the higher accreted mass. The shedding module of the ARISP model was run against the cases to verify the ice shedding locations and times. The shear adhesion strength results from Reich (28) were used in the model. A total of 40 stations were used to provide sufficient resolution for the shedding calculations.

Initial correlations were not favorable, as the ice mass predictions near the rotor tip are not good as shown in Figure 5 and Figure 6. The model over predicts the ice accretions in both cases. Correlations to experiments in the AERTS chamber are better, due to the lower tip speed of the test rotor, which is within the LEWICE validation envelope. This is important as shedding calculations rely on the ice geometry. The ice shear adhesive and cohesive areas, as shown in Figure 10, are critical to the proper prediction of shedding behavior. If the experimental and predicted shapes do not match, the experimental and predicted shedding events will also not match. Since the ARISP model over predicts ice accretions near the blade tip, the shedding frequency is also over predicted. Additional problems arise from the tip runback, shown in Figure 24, which increases bond area of the ice to the rotor.

A correction factor was therefore necessary to adjust the cohesive area at the tip sections to account for the over prediction of ice near the blade tips. This also affected the ice mass, as it is calculated based upon the cohesive area reported by LEWICE. The shear adhesion area was not modified, as the impingement limits were generally predicted accurately.

Based upon the experiments, the correction was computed by comparing the cross sectional areas of the predictions and experiments. For the three cases that shed, the correction factors are shown in Figure 35. Since ice tracings were only taken at 0.7r, 0.8r and 0.9r, the corrections were based upon photographic evidence of ice shapes.
This correction factor affects both the time and location of shedding events as shown in Figure 36. The total number of shedding events is reduced as well as the total mass of ice released from the rotor as detailed in Table 4.

The correction factors improved the shedding time and location predictions. Some error remains as shown in Table 5, however. In all cases, the experimental shedding event occurred after the prediction. In addition, multiple events are still expected based upon the model. Many more test points are required before the appropriate correction factors are created, but the basis for the shedding analysis has been demonstrated.

Table 5: Shedding Prediction Errors

<table>
<thead>
<tr>
<th>Case</th>
<th>Prediction Error</th>
<th>Time</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>25.5%</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>33*</td>
<td>14.7%</td>
<td>6.4%</td>
<td></td>
</tr>
<tr>
<td>34*</td>
<td>19.1%</td>
<td>19.3%</td>
<td></td>
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</tbody>
</table>

*Second shedding event

CONCLUSIONS

Flight into icing is known issue for rotorcraft as ice accreted on the vehicle presents large performance and safety issues. Much research has been invested into mitigating and ultimately eliminating the problem of rotor icing to expand the all weather capability of rotorcraft. This paper describes the development of an icing model and its validation to both published icing and experiments in the AERTS Facility.

The current model is accurate enough to investigate rotor icing trends and assist in the sizing of ice protection systems. The model was able to predict impingement limits within 20% of experimental values. Accreted ice shape correlations were relatively good, with larger errors at the blade tips. Initial shedding correlations were presented, including required correction factors. The shedding predictions were improved to within 25% of the experimental shedding time and location with the derived correction factors, but did not completely match the experiments.

A larger test matrix is required to fully investigate the model, however. Future work will emphasize the completion of a large test matrix, with icing clouds that match the Part 25/29 Appendix C icing envelope. The testing will provide critical data for the development of correction factors for ice cross sectional area and mass near the rotor tips. Shedding correlations will be improved with a new shear adhesion strength test fixture.
This fixture will allow various material/ice adhesion bonds to be characterized as a function of icing and material conditions.

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