

Effects of Supercooled Water Ingestion on Engine Performance

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DEDICATION

This thesis is dedicated to my family—Tom, Diane, and Kurt. Each one of them has been a major part of my success and happiness in both my life and my career.

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ABSTRACT

An aircraft will encounter freezing rain, snow, and ice during ground operation and flight. In cold conditions, ice may form on the inlet and internal stators and rotors of the gas turbine engine. When ice accumulates on blades (and/or stators), the aerodynamic characteristics of the blades change due to the altered size, shape, and roughness. This change causes the blade to no longer operate at its design point and decreases compressor performance. Therefore, characterization of the aerodynamic performance is required to define the associated losses due to the effects of supercooled liquid water ingestion. This characterization can be accomplished through analysis and test. This research developed an analysis method to calculate the aerodynamic changes on a blade due to ice accumulation and the associated degradation in performance.

The LEWICE [1] code was used to determine the thermodynamics of the freezing process when supercooled droplets impinge on a body. This droplet simulation was first used to determine the location, size and shape of the ice on the blade using atmospheric and meteorological conditions. This new shape geometry was loaded into the grid generation software, ICEG2D [17]. Once the grid was built, a Navier-Stokes flow solution solver (WIND [18]) was used to determine the new performance characteristics of the blade for the stages in question. These performance parameters included the pressure and mass loss terms. After the solution converged, the performance characteristics were analyzed to determine the effects of icing.

The coupled code process greatly increases the accuracy of determining the performance loss due to ice accretion. Analysis of the flight and icing conditions show the two major contributors to the ice accretion process were the freestream temperature and the liquid water content. After the ice accumulation process was completed, the performance loss analysis was conducted and showed 15% loss in air flow and a pressure loss that was tripled after the ice thickness reached 8% of the chord length.

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LIST OF SYMBOLS

Symbol	Definition
a	Speed of Sound (m/s)
β	Collection Efficiency
d	Droplet Diameter
d_p	Particle Diameter (m)
δ_{i2}	Kronecker Delta
MVD	Mean Volumetric Diameter (μm)
ΔT_r	Temperature Range Between Water and Ice Phases
γ	Specific Heat Ratio (c_p/c_v)
K	Inertia Parameter
k_ϕ	Thermal Conductivity of Body (W/m/K)
L	Characteristic Dimension of Body
LWC	Liquid Water Content (g/m^3)
λ	Density Ratio of Air to Particle
$\dot{m}_{clean}$	Mass Flow for Clean Blade (kg/s)
$\dot{m}_{iced}$	Mass Flow for Iced Blade (kg/s)
$\dot{m}_e$	Mass Flow of Evaporating Water ($\text{kg}/\text{m}^2\text{s}$)
$\dot{m}_f$	Mass Flow of Freezing Water ($\text{kg}/\text{m}^2\text{s}$)
$\dot{m}_{im}$	Mass Flow of Impinging Water ($\text{kg}/\text{m}^2\text{s}$)
$\dot{m}_{rb_{in}}$	Mass Flow of Runback Water into Specific Location ($\text{kg}/\text{m}^2\text{s}$)
$\dot{m}_{rb_{out}}$	Mass Flow of Runback Water Exiting Specific Location ($\text{kg}/\text{m}^2\text{s}$)

$\dot{m}_{sh}$	Mass Flow of Shedding Water (kg/m ² s)
$\dot{m}_{st}$	Mass Flow of Standing Water (kg/m ² s)
μ	Absolute Air Viscosity
N_{fstag}	Freezing Fraction at Stagnation Point
N_f	Freezing Fraction
$(N/S)_{\infty}$	Number of Droplets per Unit Area Released Uniformly Upstream
$(N/S)_i$	Number of Droplets per Unit Area Interacting with Surface Segment i
P_{t1}	Mass-Averaged Stagnation Pressure at Station 1 (Upstream of Blade)
P_{t2}	Mass-Averaged Stagnation Pressure at Station 2 (Downstream of Blade)
P_1	Static Pressure at Station 1
q''_{evap}	Evaporative Heat Loss from Surface Water
q''_{ke}	Kinetic Heat Gain to Body from Impinging Droplets
q''_{lat}	Latent Heat Gain to Body from Freezing
q''_{nc}	Net Convective Heat Loss from Body
q''_{sens}	Sensible Heat Loss (or Gain) from Surface Water
R	Gas Constant
Re_v	Reynolds Number of Air Flow Relative to Droplet
ρ_a	Air Density (kg/m ³)
$S_{current}$	Surface Distance Spacing at Current Location (m)
S_{next}	Surface Distance Spacing at Next Location (m)
σ	Surface Tension (kg/s ²)
T	Temperature
V	Free-Stream Velocity

1. INTRODUCTION

Typical turbofan engines operate over a wide range of conditions. These conditions may vary from dry to wet and hot to cold. In order to define a safe operational flight envelope, analysis and testing are performed to determine the effects of how this range in conditions will influence the performance and operability of the engine. While dry conditions are preferred when operating a turbine engine, wet conditions are unavoidable due to flight through rain or clouds at high altitudes. During cold, wet conditions, ice may accumulate on the inlet or the engine rotors and stators. The presence of the ice and associated liberation could adversely affect engine performance and operability.

Turbine engines are designed to operate over a specific operating envelope based on the compressor and turbine characteristics. When these characteristics are changed, the performance of the engine will change and may have adverse effects on the operability of the engine. These effects must be defined through test and analysis over the conditions that are susceptible to ice formation. Previous work has shown various negative icing effects through either experimental work or computational work primarily for large wing type airfoils.

In order for a turbine engine to operate at its design point, all of the components of the engine must operate within their unique design constraints. This means that the compressor must provide the design compression per stage that is necessary for the air and fuel to mix in the combustor which then must deliver the correct conditions to

properly expand the air through the turbine to drive the compressor and fan through the nozzle to get thrust. The principle factors influencing the desired compression from a particular stage are the size and shape of the blades in both the rotor (rotating airfoils) and stator (stationary airfoils). The design of these airfoils is affected by the pressure, temperature, and the air incident angle.

Only recently has analysis been applied to determining the adverse effects of icing on a turbine engine. However, there have been a large number of studies conducted to determine the effects of change in the conditions around an aircraft wing to understand the performance of lift vehicles. The major differences between an aircraft airfoil and a compressor blade are the much more complex geometry and the rotational velocity of the compressor blades. With ice build-up on these airfoils, the size, shape, flow angularity, and even the roughness of the surface causes the performance of these stages to decrease.

After analysis of the data from past engine failures, it was shown that icing events were causing engine stalls and flame-outs. Systems were then implemented to try to counteract ice build-up or prevent it from occurring. The two types of systems that are typically used are the anti-ice system and the de-ice system. The anti-ice system can be turned on when the plane is approaching a condition that has a high probability of ice build-up on the engine. Typically, when this system is turned on, hot air is pulled from a stage in the compressor that has very hot and very high pressure air and used to heat either the front fan blades or the inlet. However, a couple of the problems with this system are that ice can accrete in other places besides the very front of the engine, and the

system can be turned on too late causing it to become more of a de-ice system (which is a system that is only turned on once ice has built-up).

A de-ice system is used when sensors on the engine indicate that ice is beginning to form on a particular blade or stage. The system pulls hot air from a higher stage in the compressor to heat the section to melt the ice enough for it to fall off. This type of system is less common due to the fact that as the ice melts, large chunks of ice can fall off and travel through the engine causing damage to the engine. Additional effects of ice travelling through the engine lead to performance reduction through possibly ice accretion at farther downstream stages of the high-pressure compressor where the hot air cannot be used to heat the blades or stators.

In an attempt to better understand the effects of icing on turbine engines, experimental testing can be performed. The advantages of simulated ground testing are the ability to control the flight and icing conditions that the engine will undergo and the instrumentation to measure the overall performance and operability effects. To supplement the test plan and to better characterize test results, simulations are employed. Therefore, running a computational model in conjunction with testing is the best method for determining the icing effects. An additional advantage to running a model before or during testing is money savings since the worst cases can be determined before the test is ran and lead to more efficient air periods.

Since icing consists of multi-phase flow and requires a high fidelity solution, a computational program was necessary to make the calculations and predictions of the ice

build-up. The difficulty of performing calculations with multi-phase flow is the different characteristics of particle reactions and behaviors in the different phases (i.e. the conservation of momentum equation becomes very difficult to define and solve). The NASA program LEWICE was chosen to complete the necessary calculations for the analysis. LEWICE uses a Lagrangian particle motion method to determine the trajectories of the ice particle along with a potential flow code to calculate the gas path. Since the analysis of ice crystal effects is to be studied, the two-phase coupling that occurs in the engine must be understood and an analysis of the latter stages in the compression system is conducted. This two-phase coupling occurs since the large ice crystal size or droplet size approaching 200 μm displaces a large enough volume, with respect to the air, that will have a significant effect on the air as it passes through the engine. Treating these further stages as their own system, a better understanding of the effects of large particles on a compressor stage can be gained.

2. PROBLEM STATEMENT

The objective of this research is to couple the LEWICE ice code with the WIND gas flow code. This coupled code will then be used to determine the effects of supercooled liquid ingestion effects on a turbine engine compression system. Since the output from WIND gives the performance of the stators (and/or rotors) of the compression system, this can be taken as an estimate of the overall engine performance. In order to get more accurate overall performance degradation, a coupling with an engine code that allows for the disruption of the flow (or a code that can account for the flow and pressure losses due to the ice accretion) was outside the scope of this thesis. However, a correlation or loss factor can be analyzed. Experimental data, as available, and past computational fluid dynamics (CFD) simulations combined with known engine performance was used to validate the results obtained using the modified code.

3. LITERATURE SEARCH

3.1 ICE SCALING

The technique of ice scaling is used to study the effect of ice accretion effects on a scaled object and an important first step in understanding the effects of icing on an airfoil. Also ice scaling is used to derive the scaling conditions (shown below), which is important in order to simulate an icing encounter in flight. This method also provides the basis for which ice accretion principles and definitions are based. Also when performing ice scaling tests, an airfoil model, similar to those that make up the stage of interest in an engine, is used. However, there are changes that are required in order to develop an ice accretion code that is capable of determining accurate ice accretion on a rotor or stator of a turbine engine. Bilanin [4] describes some of these modifications.

A scaled object is one that is similar in geometric shape and reasonably identical surface conditions as the original object. Scaling is performed to be able to run an experiment without causing unnecessary damage to the original object and to save cost. Ice scaling will be used in conjunction with the scaling equations from Ruff [5] and Bartlett [6].

When icing occurs, it is assumed that it accretes such that each layer forms on top of the previous layer. Layering is important, but the problem is the surface needs to have the same shearing and ice holding properties as the blade surface being simulated.

Icing scaling consists of two basic types. Those types are subscale model testing and parameter substitution testing. Subscale model testing has the advantage of being

able to perform testing on a much smaller scale, which can be accommodated by smaller test facilities. Parameter substitution extends the testing capabilities of the test facility where the experiment is being conducted (or the test technique that is being used). When testing at a ground-based facility, the duplicated flight conditions are total temperature and pressure, droplet size, duration, and liquid water content.

During an icing test, there are several major areas of concentration. These areas are flow field around the article, surface thermodynamics, ice collection, and droplet trajectory and impingement characteristics. Therefore, in order to determine the scaling similarity to be maintained and ensure it is correct for the areas of concern, Ruff [5] uses an approach for ice scaling that utilizes the five scaling parameters described below.

- The modified inertia term, K_o (Figure A-1), will show the ability to attract and collect droplets in the flow path. K_o is dependent mainly on the relative velocity and size of the drops along with the collection geometry.
- The freezing fraction, n (Figure A-3), is the relationship that determines the amount of water that is actually freezing to the object. The closer the freezing factor is to one, the faster the freezing of a water particle will occur as it flows along the surface of the object.
- The accumulation parameter, A_c (Figure A-2) is the parameter that relates the rate of catch to the velocity, duration, efficiency and liquid water content terms. However, this term only determines the accumulation and not the amount of ice that is actually on the object since it does not account for ice growth.

- The air energy driving potential is Φ (Figure A-4). Φ also accounts for the heat loss from evaporation by taking the ratio of this heat loss and the convective heat transfer coefficient.
- The water droplet driving potential, Θ (Figure A-5), is a term that relates the total enthalpy of the water to the specific heats of the droplets.

Figures A-1 to A-5 (in Appendix) show the effect of changing velocity, static pressure and temperature have on liquid water content, static temperature, droplet size, and icing time by keeping the respective scaling parameter (i.e. K_o , N , etc.) constant. It is seen with so many factors having large effects on the engine performance, a cheaper and more efficient method for accounting for icing is necessary.

3.2 ICE ACCRETION

AGARD Report 344 [7] describes the effects of ice accretion on wings and other surfaces that are susceptible to ice build-up during flight and while on the ground preparing for flight. Also the authors go on to describe the techniques behind icing simulation in several different testing environments (i.e. ground testing and spray tanker experiments).

In order to understand the aerodynamics and thermodynamics of ice accretion, the principles behind general ice accretion must be understood. First, there are several different types of ice that can form, and a few will be discussed. An ice crystal is considered to be solid of any size but typically less than 0.1mm. A droplet differs from an ice crystal in that it is still considered to be liquid. Riming or glazing (Figure 1 and Figure 2) is the process which represents the growth of ice through supercooled water droplet collection on solid surfaces. Rime ice is simply smooth layers of ice extending the chord length of the blade. Glaze ice is characterized by the double horn shape that the ice takes due to the runback of the water particles on the blade from the stagnation point. This process of rapid growth of supercooled droplets causes problems for aircraft as well as aircraft engines.

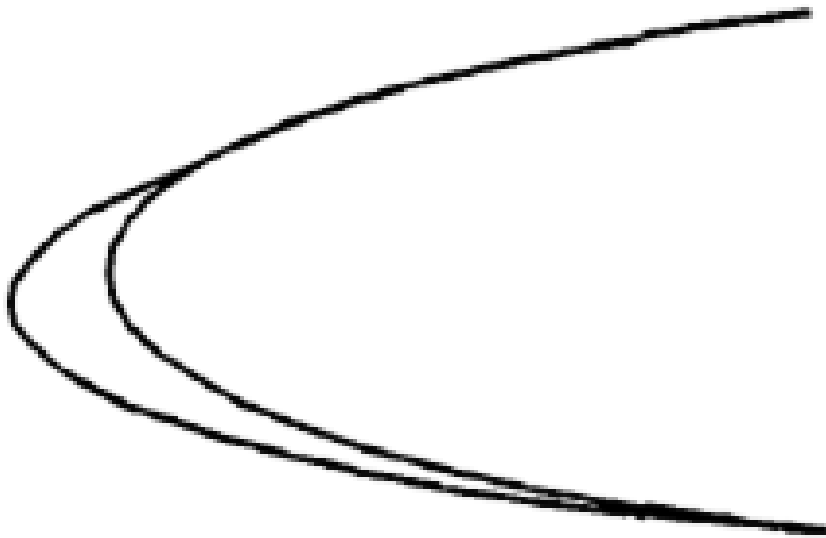


Figure 1: Rime Icing [7]

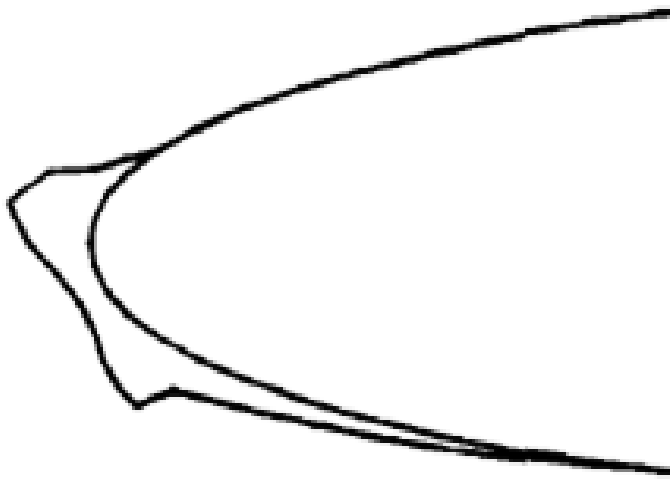


Figure 2: Glaze Icing [7]

The AGARD Report 334 [7] also describes the different types of ice accretion and how these form. The type of ice accretion that will form on engine surfaces will greatly depend on the droplet size and the distribution of those droplets. Consider first a droplet size between 200 and 500 microns. This type of droplet is considered drizzle, and it has a large impact on icing problems for engines and aircraft causing several incidents (i.e. ATR-72). Research into this problem is still being conducted.

Drizzle has only been demonstrated to affect engine performance through a water ingestion issue and not icing (only effects the operability due to the build-up on the spinner and damaging the blades due to impact). However, droplets that are only a few microns in diameter, and do not follow the streamlines, will begin to build up on a solid surface quickly. One type of ice that can accrete is riming.

Riming occurs primarily under low LWC (liquid water content) and cold air conditions. This is also the simplest form of ice build-up on an engine surface since it merely attaches and remains where the droplets impact the surface (i.e. the droplets freeze immediately on impact). Rime ice is the most benign ice shape since it extends the chord of the airfoil and can change the velocity vector.

Glazing is another form of ice. Glazing, however, occurs when unfrozen water is also present in the zone of impact. The main hazard of glazing is the unfrozen water that runs downstream of impact and freezes (i.e. the freezing process is not immediate). This causes some very complex and wide (perpendicular to the airflow and chord) ice shapes on the airfoils. Also droplets will coagulate with other droplets on the surface as the water collects and causes an increase in the aerodynamic roughness. This aerodynamic roughness will in turn cause an increase in the convective heat transfer coefficients which will increase the growth of ice thickness downstream of these discrete droplet areas. The growth of the ice can be reduced or removed by using a de-icing system; however, this process could lead to some residual ice formation in addition to the blade leading edge causing further aerodynamic and thermodynamic effects. The final ice accretion type that can cause problems that is more serious while on the ground than in the air is frost, freezing rain, and snow freezing. This type of icing simply causes the increased surface roughness and weight.

The effect of surface roughness and change in geometry due to ice accretion on an airfoil is seen in Figures 3 and 4. These charts show how the coefficients of lift and drag are affected by ice accretion. The coefficients are shown in order to understand how icing affects the performance of airfoils, which has a direct impact on the performance of the engine.

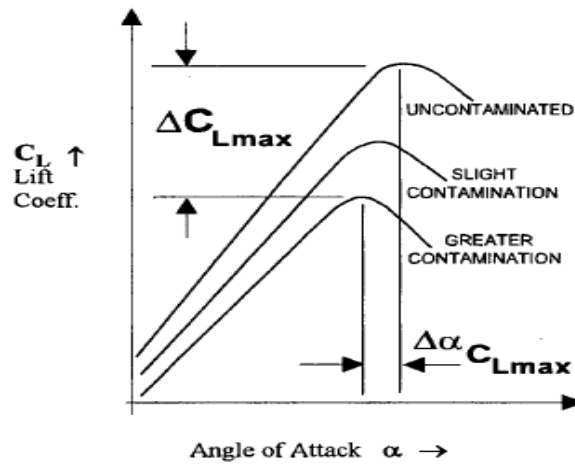


Figure 3: Ice Contamination Effect on Lift [7]

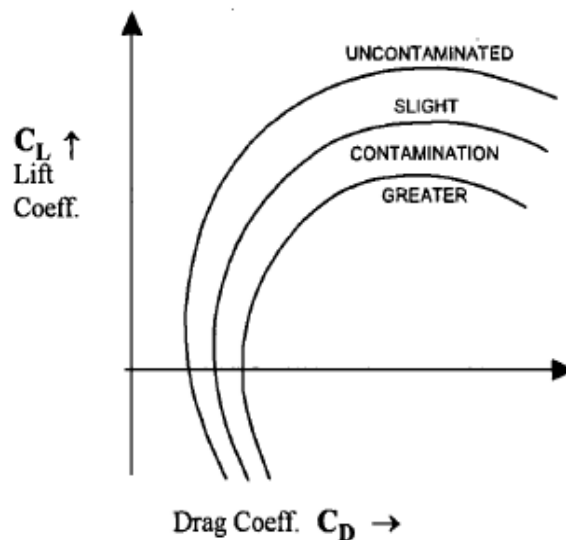


Figure 4: Ice Contamination Effect on Drag [7]

3.3 EFFECTS OF ICE ACCRETION ON PERFORMANCE AND OPERABILITY

3.3.1 EXPERIMENTAL STUDIES

Olsen, Shaw, and Newton [8] performed an experimental study to understand the effects of the different types of ice shapes on the performance of a NACA 0012 airfoil. These effects were primarily focused on the drag increase on the airfoil. However, there were other results obtained concerning surface roughness and ice structure. This study was performed in order to improve the ice accretion modeling and theories being developed. The test was conducted in the NASA Icing Research Tunnel and used a very wide range of test conditions in order to understand many icing phenomena. They discovered that the greatest effect on ice shape and structure is temperature (shown in Figure 5).

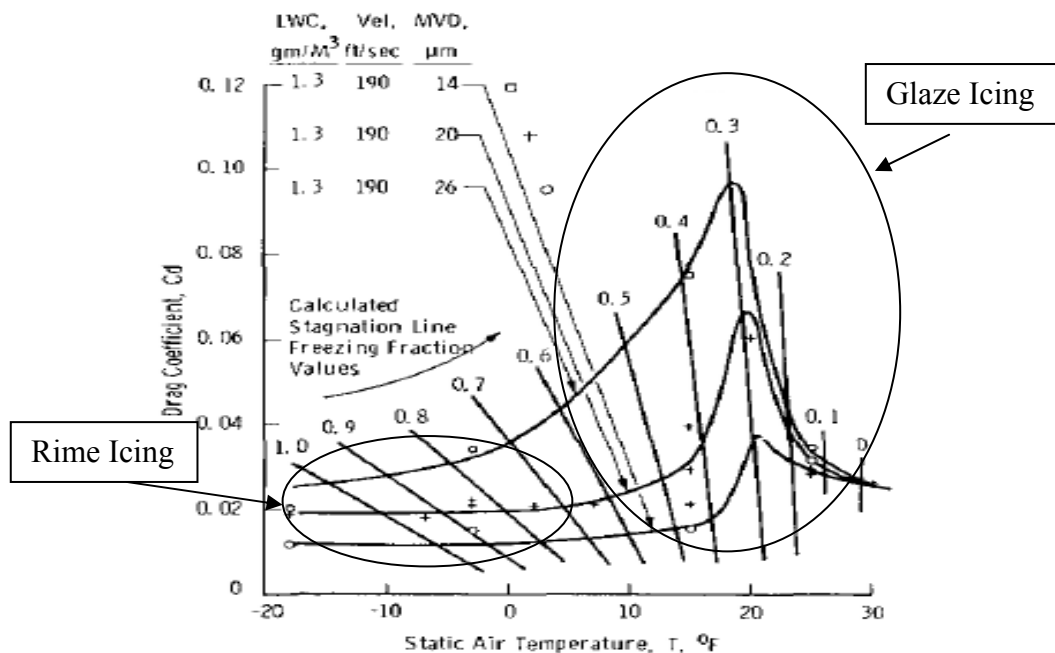


Figure 5: Effect of Static Air Temperature and Droplet Size on Ice Shape Drag [8]

At the coldest temperature, rime ice typically forms; however by changing temperature or LWC, glaze ice can begin to form for the same droplet size. The ice structure was studied using photographs and ice samples taken and looked at under polarized light. Droplet size was found to have a large effect on the way glaze ice forms. For example, the angular location of the upper surface horn changes due to the droplet size. Also the ice shape and resulting drag are also changed dramatically by the larger droplet sizes. While droplet size was found to have a large effect on glaze ice, it was found to have a small effect on rime ice. The only rime condition parameter that was affected by the droplet size was the increase in collection efficiency of the larger drops. The effect of the roughness on the ice surface was found to have a much larger effect on the glaze ice than on the rime ice, which almost never gets rough when comparing to glaze. The glaze ice does however increase in roughness very quickly at the beginning and then slows down as the test progresses. Finally a study to determine the effect of ice removal on the performance of the airfoil was conducted. It was found that suction side glaze ice horn was more important than the pressure side horn of glaze ice formation (Figure 6).

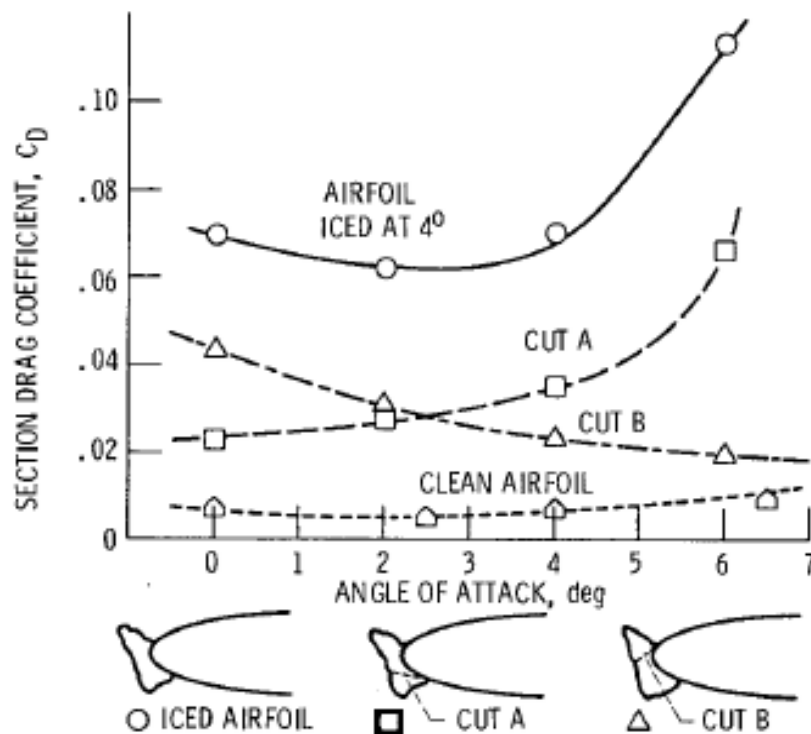


Figure 6: Effect of Partial Ice Removal [8]

Jackson, Cronin, Severson, and Owens [9] performed a study using the Ludlam Limit Considerations on cylinder ice accretion in order to determine the performance of ice detectors. The Ludlam Limit is the point at which water can no longer accrete as ice on an object and begins to shed. This study would also perform a comparison between several different studies that were conducted over the years to determine the best estimation for ice accretion. The first was to look in what components that should be considered in the energy balance equation. The determination was to include six terms. The terms were the heat loss of convection, heat loss by evaporation, heat loss by warming the fluid, heat gain due to latent heat of fusion release, heat gain due to frictional forces, and heat gain due to the kinetic energy of the liquid. During the derivation of these equations, a representation of evaporation to account for the heat

transfer coefficient change when transferring from laminar flow to turbulent flow is necessary. The results found show that by increasing the static air temperature, the LWC must decrease to obtain similar ice formations (shapes). However, if the freezing fraction was set to zero instead of 1, the Ludlam Limit would be reached and no impinging droplets will accrete on the surface.

3.3.2 NUMERICAL STUDIES

Cook [10] discusses a model that will determine the maximum air static temperature where ice may form on a surface in order to better understand when it is necessary to use an anti-ice or de-ice system. The model used to perform the analysis was the AEDC1DMP particle trajectory code, which was developed at AEDC. The author first considered the dry air, adiabatic, compressible flow theory applied to a cylinder. However, this theory was shown to be less accurate since it did not take into account evaporative cooling. The author then makes an adjustment to the theory using NACA TN 2914 [11] and performed an initial comparison to experimental and dry theory data (shown in Figure 8). The next step in Cook's paper was to analyze the effect of test section humidity. The results from this analysis and adjustment are shown in Figure 7.

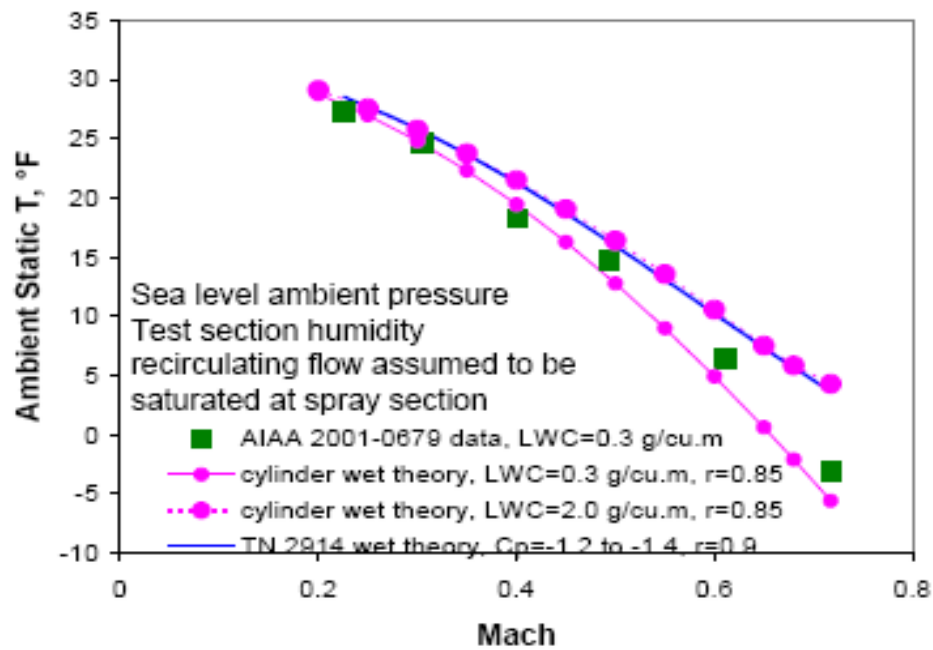


Figure 7: Maximum Temperature for Ice Accretion Corrected for Humidity [10]

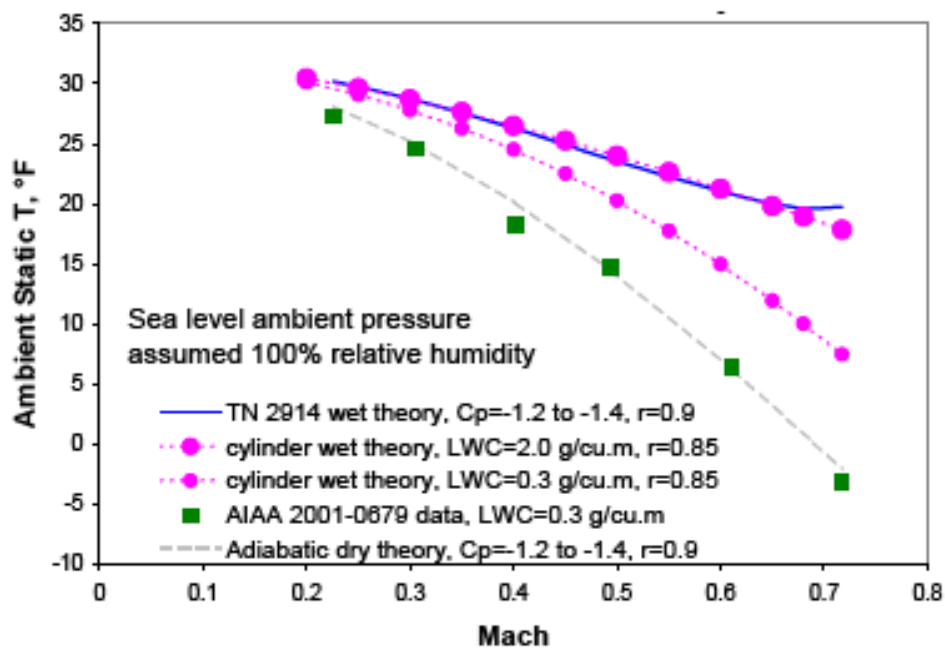


Figure 8: Maximum Temperature for Ice Accretion [10]

Gray [12] performed an analysis to develop an equation that determined the changes in the drag coefficients due to ice accretion changes on an airfoil. In addition to the drag coefficient changes, he also determined the changes in lift and pitching-moment coefficients. The relationship was focused on the principle that there is a set of known ice and flight conditions available. These conditions were icing time, airspeed, air temperature, LWC, impingement efficiencies, chord, angles of attack, and radius of curvature for the leading edge. This study does not account for several important factors when looking into icing but it does give a good understanding of what type of ice forms and an estimate on the size and shape of the ice formation.

Papers written by Hale, Klepper, and Hurwitz [13] and another by Hale, Klepper, Hurwitz, and Davis [14] discuss the numerical technique in combining the Meanline Code, Multiphase Code, and the AEDC1DMP code. This coupling was done in order to determine the effects of steam ingestion on an engine. These papers provide a good understanding of how the three separate codes can be combined to determine the multiphase effects of water in the compression system of an engine. The authors used the 1-D mean line code to model the air and water vapor through the compression system and the multiphase code modeled the liquid water and vaporization process. The exit conditions of the turbomachinery portions are updated with the change in total pressure and temperature that is calculated by the multiphase code to give the final results from the coupling.

Das, Hamed, and Basu [15] present results from an analysis conducted using the LEWICE code from NASA to determine the effects of ice accretion on a high bypass

turbofan engine rotor. The results that are compared with a clean rotor are the inlet temperature, rotor speeds, and ice shape along the span of the blade. The method that was used to determine the interaction was a Eulerian-Lagrangian approach for the trajectory and flow field. The results from this analysis determined that thicker ice accreted at the leading edge of the blade and on the pressure surface near the hub. Also that ice build-up increases as the engine speed is decreased (due to the reduction in forces upon the ice) and depends greatly on the inlet total temperature changes.

The analysis conducted by Rios and Cho [16] was performed in order to identify and analyze the effects of ice crystal ingestion through the engine core. They identified that ice crystals may obtain a size up to 200 μm in diameter and have a liquid water volume of up to 9 g/m^3 . Also the event that was to be identified was the compressor surge or combustor flame out (which could occur during flight due to latter stage ice accretion). The main focus of their research was to determine how far the ice crystals go inside the engine core for this second stage accretion. The results from Rios' paper show that a one-way coupling of the flow will not be effective since the large particles will have a significant effect on the flow itself. Also the first crystals impacting the stator blades will melt and not be an issue of concern; however, due to the slush that forms from the first crystals which cools the blade, the next ones that impact the blades will begin building up on the pressure surface. This build-up begins to form glaze ice with a horn that blocks the air flow and leads to engine surge or flame out.

3.5 CONCLUSIONS OF THE LITERATURE SEARCH

For many years, ice accretion on aircraft wings has been reviewed. Only recently have experimental and numerical studies have been done to account for the ice accretion on a blade to determine build-up and ice shapes for many different conditions. However, there has been little research to determine the performance effects that ice build-up have on the components of a compression system susceptible to ice accretion (i.e. first several stages). In order to determine the trajectories of the ice particles through an engine, an Euler-Lagrangian method was the most commonly used and most accurate. Therefore, a technique that accounts for changes due to ice accretion on rotor and stator blades is needed to determine the performance of a turbine engine. In order to accomplish this technique, the LEWICE code was used in order to determine the ice accretion on a blade and the resulting compressor performance characteristics. In addition, using this code as an analysis tool, the effects of ice accretion and ingestion on performance was studied.

4. APPROACH

4.1 COUPLING OF CODE

LEWICE has the capability to determine the performance loss due to icing using a potential flow solver; however, a more accurate method would be to use a RANS (Reynolds Averaged Navier-Stokes) solver to determine the flow solution. Therefore, WIND was chosen as the flow solver. In order to have the capability to run WIND, a grid was generated for each new ice accretion step. This was done using ICEG2D. ICEG2D is grid generation software developed by NASA in order to run LEWICE with a flow solver like WIND. Figure 9 shows how this coupling of code was performed.

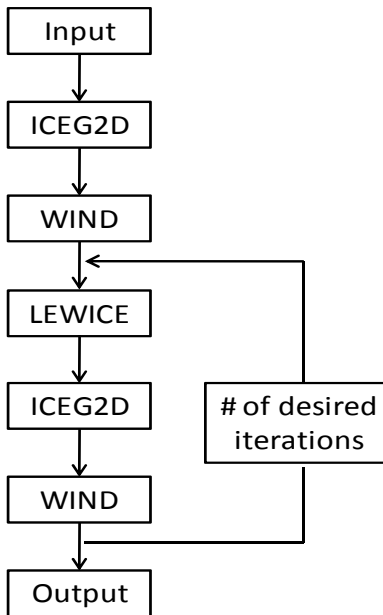


Figure 9: Coupled Code for Determining Performance Degradation

4.2 BACKGROUND

4.2.1 TURBOFAN ENGINE

Figure 10 and Figure 11 from Rios and Cho [16] show both the supercooled water and crystal ice accretion problems on a typical turbofan engine. The supercooled water accretion problem (Figure 10) occurs as either glaze or rime ice and only builds-up on the outer portions of the engine and first stages. This is a problem due to the possibility of the ice breaking off and causing damage to the engine components. Another result of supercooled water accretion is the performance degradation on the first stage (or fan) blades.

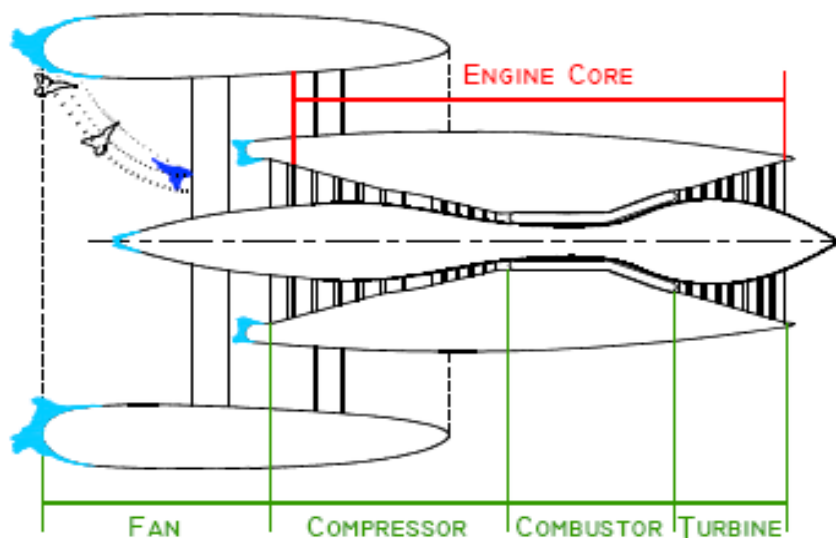


Figure 10: Supercooled Water Problem on Turbofan [16]

The second problem is the crystal ice ingestion problem (Figure 11). This problem was identified when core icing events (stalls or flame outs) occurred for unexplained reasons. The possible cause of these events is the break-up and melting of these crystals during the first several stages of compression and the resulting cooling effect this water has on the blades in later stages. This cooling of the blades by the water allows them to become more susceptible to the ice accretion similar to that of the first stage during supercooled water conditions. Since the icing problems have been identified as a problem for the core path of the flow, the bypass flow will be ignored in this study.

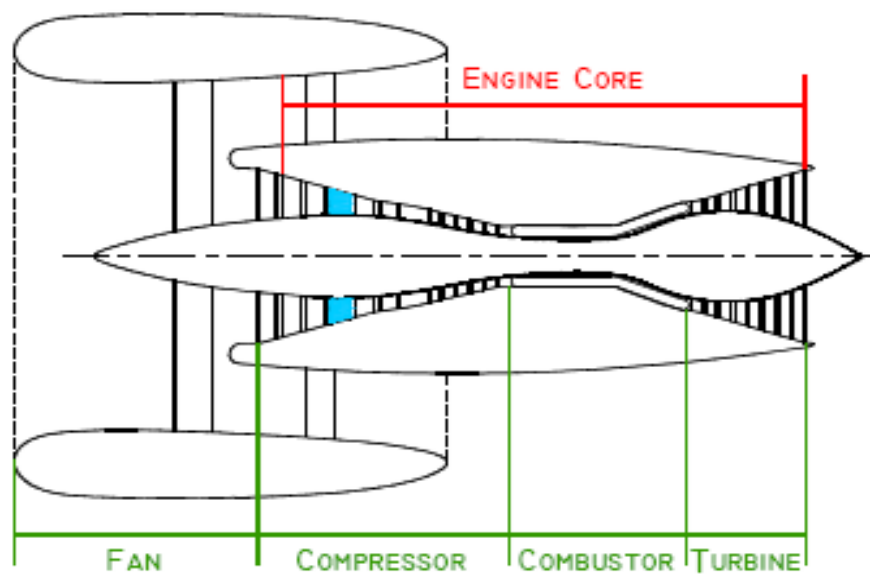


Figure 11: Crystal Ice Ingestion Problem [16]

4.2.2 LEWICE

LEWICE is an ice accretion prediction code that consists of four modules in order to determine the ice build-up on a surface exposed to airflow with supercooled water droplets. The modules are the following: 1) flow field calculation, 2) particle trajectory and impingement calculation, 3) thermodynamic and ice growth calculation, and 4) modification of the current geometry by adding the ice growth on it. These modules follow steps to find the performance of the given blade. The very first step in finding performance characteristics is to find the location, size and shape of the ice. The benefit to using the LEWICE code, in order to perform this task, is the ability to analyze many different systems (including anti-ice or de-ice system) and find the worst conditions (i.e. where the most ice will build-up on the engine and the atmospheric conditions where this will occur) for very little cost instead of the immensely larger cost of running a ground test.

LEWICE is a model to determine the thermodynamics of the freezing process when supercooled droplets impinge on a specified body. It uses both atmospheric and meteorological conditions to determine how the ice will accrete on the body. The atmospheric conditions are temperature, pressure and velocity, and the meteorological conditions are the droplet size (defined as the Mean Volumetric Diameter, MVD, in this thesis), liquid water content (LWC), and the relative humidity. It also follows the icing model laid out by Messinger [2] to determine the ice growth rate.

4.2.3 ICEG2D

ICEG2D was also developed by NASA in order to automate the CFD simulations of ice accretion by creating a grid that can be fed directly in a RANS flow solver. This is done by performing four primary functions. The first is to generate a grid-ready surface definition. This is done by distributing points on the surface of the iced blade and increasing the number of points in areas of large geometry changes in order to create a surface distribution with high accuracy. The next step is to create the grid based on this surface definition. Creating a grid for such a complicated geometry is extremely difficult. The technique used to reduce this difficulty is a marching technique and the use of a C-type grid due to the improved resolution at the airfoil trailing edge. By using this marching method, the transient portion of the solution can be removed quickly and steady-state flows can be solved. The final two steps of the grid generation are to create the input files necessary to run WIND and LEWICE. These files are re-formatted from user defined input files that include the flight and icing conditions, in addition to other necessary grid and output selection information.

4.2.4 WIND

WIND was created under the NPARC (National Project for Applications-oriented Research in CFD) Alliance, which consists of NASA Lewis Research Center and Arnold Engineering Development Center (AEDC). WIND was developed in order to provide an applications CFD tool by combining existing CFD solvers. By combining several pre-existing solvers, it has many application and uses; however, the primary function of

WIND is to serve as an Euler and Navier-Stokes flow solver. Some other capabilities utilized are the ability to apply a Spalart-Allmaras turbulence model and boundary condition models in order to accurately determine the flow around a blade with a complex geometry due to the ice accretion process.

4.3 APPROACH IMPLEMENTATION OUTLINE

The following is an outline for the proposed approach to determine the performance effects of supercooled water on engine performance:

1. Implement the LEWICE code.
2. Perform analysis of initial check runs with provided validation results to ensure code is functioning properly using the potential flow solver.
3. Perform check of grid-based ice accretion and performance loss check runs.
4. Compare grid-based and potential flow solutions to determine most accurate and best technique to perform analysis.
5. Determine best approach to coupling all three codes necessary.
6. Use coupled code to evaluate the effects of several different flight and icing conditions on the performance of an engine.
7. Analyze correlation and performance loss characteristics of the affected stages.
8. Compare final data package results with data collected using other numerical results and experimental results where available.

4.4 MODELING APPROACH

4.4.1 COMPUTATIONAL DOMAIN

In order to determine the performance loss across a stage, a computational domain was set up (Figure 12), and the assumption was made that the same performance can be translated across all the blades in that stage. Since most past research and code validation was conducted using NACA wing airfoils, there was only a limited number of compressor blades to choose from to conduct the necessary analysis. Therefore, the stage 67A stator blade shown in Figure 13 was chosen to be the best choice for the analysis. Blade 67A is a replacement to the blade 67 that originally had a double-circular arc profile. The new profile of the blade provides for better adiabatic efficiency and fewer stalls.

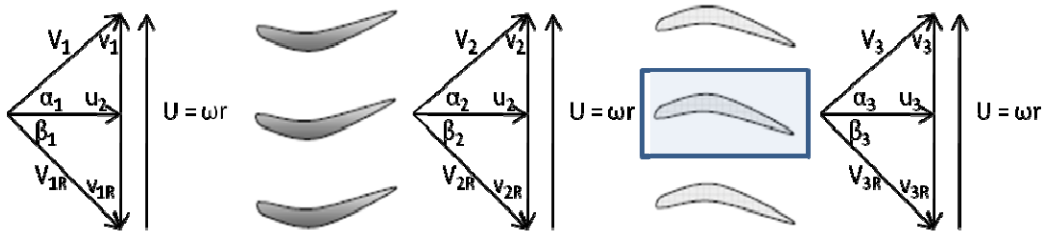


Figure 12: Velocity Diagram and Computational Domain

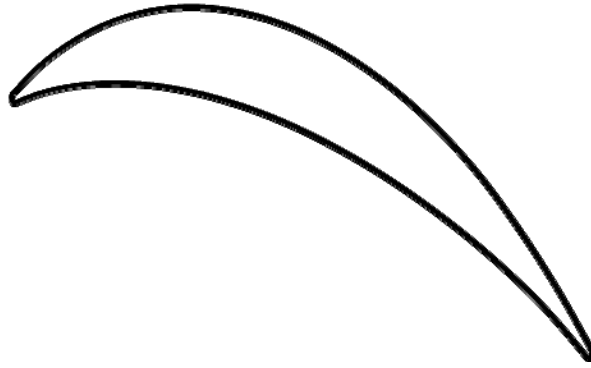


Figure 13: Stage 67A Cross-Section

4.4.2 TRAJECTORY

The first step in determining the ice accretion was to calculate the trajectories that the water particles are traveling. The primary force acting upon these water droplets is drag. LEWICE uses a quasi-steady approach for a small spherical droplet. Shown in Equation 1, Papadakis [19] gives a simplified form of the equation of motion that is used to determine these trajectories. In this equation U_i represents the velocity of the particle, V_i is the velocity of the air, Re_v is the Reynolds number, C_D is the drag coefficient, g is the gravitational constant, L is the characteristic length of body, σ is the density ratio of air to particle, K is the inertia parameter of droplet, δ_{i2} is the Kronecker delta, and V_∞ is the free stream velocity

$$\frac{dU_i}{dt} = \frac{C_D(Re_v)Re_v(V_i - U_i)}{24K} - \frac{(1 - \lambda)gL\delta_{i2}}{V_\infty^2} \quad (1)$$

In order to derive Equation 1, several assumptions have to be made.

- 1) The flow is quasi-steady-state
- 2) The drag coefficient is for a stationary sphere
- 3) The particles have no moment or lift and are solid and spherical
- 4) The droplets do not interact with each other
- 5) Viscous effects are not considered

4.4.3 DROPLET BREAK-UP AND SPLASHING

In addition to water particles simply impinging and freezing on the surface, some particles may only partially impinge. This partial impingement was caused by splashing and droplet break-up. Both were determined to be a small issue since the smaller droplets may break into very small droplets and evaporate before re-attaching to the surface of the blade. Splashing and droplet break-up are considered a larger issue for droplet sizes greater than 100 μm . However, for the most accurate approach, these issues cannot be ignored and were calculated and taken into account. The amount of splashing was calculated by subtracting the local mass fraction of the water loss due to splashing from the local collection efficiency.

Before a droplet break-up occurs based on shear flow (i.e. relative velocity between the air and droplet), it will first change from a sphere to an ellipsoid. This change in shape changed the drag coefficient which alters its trajectory. In order to determine if a droplet breaks up after each step, the Weber number was calculated. The Weber number, We , compares the water's inertia to the surface tension. The calculation for the Weber number, as a function of air density (ρ_a), velocity (V), droplet size (d_p), and surface tension (σ), is shown in Equation 2. For a Weber number of below 12, droplet break-up will not occur.

$$We = \frac{\rho_a V^2 d_p}{\sigma} \quad (2)$$

4.4.4 COLLECTION EFFICIENCY

Once the trajectories were calculated and droplets began interacting with the blade, a running total of attached particles was maintained. Therefore, the collection efficiency, β , was calculated. The collection efficiency is defined by the ratio of droplets released upstream of the blade, $(N/S)_i$, with the droplets interacting with the surface of the blade, $(N/S)_\infty$, (shown in Equation 3).

$$\beta_i = \frac{\left(\frac{N}{S}\right)_i}{\left(\frac{N}{S}\right)_\infty} \quad (3)$$

4.4.5 ROUGHNESS HEIGHT

Since ice accretion is largely dependent on the surface and boundary conditions of the blade, the model must account for the roughness height (sand-grain roughness height). LEWICE calculates this as a function of the freezing fraction at the stagnation point ($N_{f_{stag}}$, as determined from the melting point temperature (T_{mp}), temperature range between phases (ΔT_r), and the temperature at a given surface location, (T_s)) and empirical data from experimental measurements. Equation 4 and Equation 5 shows the correlation.

$$x_k = \frac{1}{2} \sqrt{0.15 + \frac{0.3}{N_{f_{stag}}}} \quad (4)$$

$$N_{f_{stag}} = \frac{T_{mp} + \Delta T_r - T_s}{\Delta T_r} \quad (5)$$

4.4.6 MASS AND ENERGY BALANCE

The two most important conservation equations are the mass and energy balance. The energy balance (Equation 6) determined the heat gain and loss at each location. It also finds the available energy for freezing water. Without calculating the largest contributors (net convective heat transfer (q''_{nc}), kinetic energy gain to body from impinging droplets (q''_{ke}), evaporative heat loss from surface water (q''_{evap}), latent heat

gain to body from freezing (q''_{lat}), and the sensible heat transfer from surface water (q''_{sens}) to the energy balance accurately, the accretion process would not be valid.

$$-\left(k_{\varphi} \frac{\partial T}{\partial \varphi}\right)_{\varphi=0} = q''_{nc} + q''_{evap} - q''_{ke} - q''_{lat} \pm q''_{sens} \quad (6)$$

The mass balance determined the amount of water that freezes at each location. In addition to determining the ice that builds up immediately upon impact, it also determines the amount of water that runs down the blade and freezes somewhere other than the blade leading edge. Equation 7 shows how the mass balance is determined from mass flows from the following portions: the impinging droplets ($\dot{m}_{im}$), the runback water into an area ($\dot{m}_{rb_{in}}$), the runback water out of an area ($\dot{m}_{rb_{out}}$), the evaporating water ($\dot{m}_e$), the freezing water ($\dot{m}_f$), the shedding water ($\dot{m}_{sh}$), the standing water ($\dot{m}_{st}$), the ratio of the change in spacing to the current location ($\Delta s_{current}$), and the change in spacing to the next location (Δs_{next}).

$$\dot{m}_{im} + \dot{m}_{rb_{in}} = \dot{m}_e + \dot{m}_f + \dot{m}_{rb_{out}} \frac{\Delta s_{next}}{\Delta s_{current}} + \dot{m}_{sh} + \dot{m}_{st} \quad (7)$$

4.4.7 FLIGHT/ICING CONDITIONS

A test matrix that covers the major components of ice accretion was developed from past research and the AGARD report [7]. Shown in Table 1 are the flight and icing parameters analyzed.

Table 1: Summary of Flight Conditions Analyzed

Altitude ft	Mach Number -	Static Temperature °R	Static Pressure psia	Air Speed ft/s	Droplet Size μm	Liquid Water Content g/m ³
0	0.3135	455.67	14.7	328.08	20	0.55
0	0.3135	455.67	14.7	328.08	50	0.55
0	0.3088	469.67	14.7	328.08	20	0.55
10000	0.3135	455.67	10.106	328.08	20	1.5
10000	0.3135	455.67	10.106	328.08	20	0.55
10000	0.3135	455.67	10.106	328.08	50	1.5

4.5 PERFORMANCE DEGRADATION

Once the ice accretion process was completed and the flow solution calculated, the performance degradation was determined. Lee and Loth [20] define two primary methods for determining performance loss due to ice accretion. The first is the pressure loss across the blade (a ratio comparing the difference in the stagnation pressures upstream (P_{t1}) and downstream (P_{t2}) to the difference in the stagnation pressure and static pressure upstream (P_1) shown in Equation 8). The second is the mass flow loss through the stage (the ratio of the iced mass flow rate ($\dot{m}_{iced}$) to the clean mass flow rate ($\dot{m}_{clean}$) shown in Equation 9).

$$\omega = \frac{P_{t_1} - P_{t_2}}{P_{t_1} - P_1} \quad (8)$$

$$\phi = \frac{\dot{m}_{iced}}{\dot{m}_{clean}} \quad (9)$$

5. RESULTS

In order to determine the full effects of supercooled water ingestion on the performance of a turbine engine, an analysis on all aspects of the accretion process was considered. The primary focus of this analysis was the collection efficiency, ice accretion profile, flow fields, and the blade performance degradation. Also since there are numerous factors that can affect how ice builds up on a blade, the results shown were divided into five sections. By only varying one condition at a time and showing its effects, the largest factors in ice accretion and performance loss were determined.

5.1 TIME VARIANCE

The first parameter chosen to be varied was time. By analyzing the effects of time on ice accretion, pilots can be trained to turn the anti-ice or de-ice systems on before the performance of the blades causes severe efficiency loss or builds large enough to damage the engine. In order to determine how the ice was accreting on the blade, the collection efficiency was analyzed along with the ice build-up (shown in Figure 14 and Figure 15). From these figures, it is seen that the collection efficiency provides an accurate measure of the ice thickness (the trends are very similar); therefore, further analysis of the thickness is unnecessary. The wrap distance shown in the figures of this thesis was defined as the distance from the trailing edge around the blade.

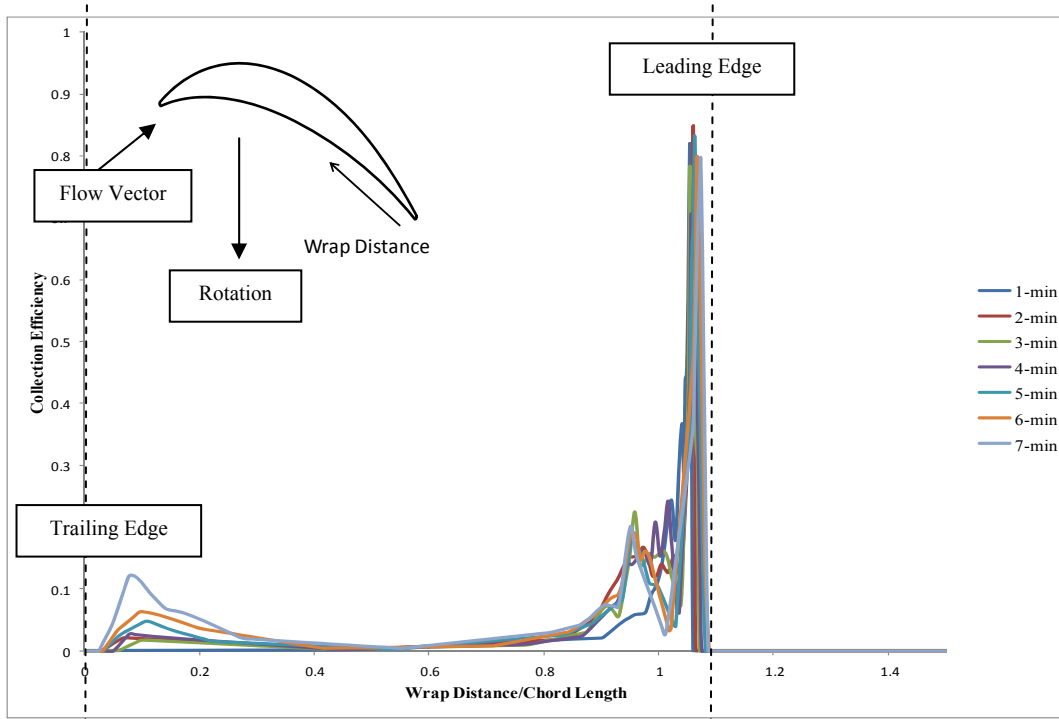


Figure 14: Collection Efficiency for Time Variance at 0ft/Mach = 0.3135/455.67°R

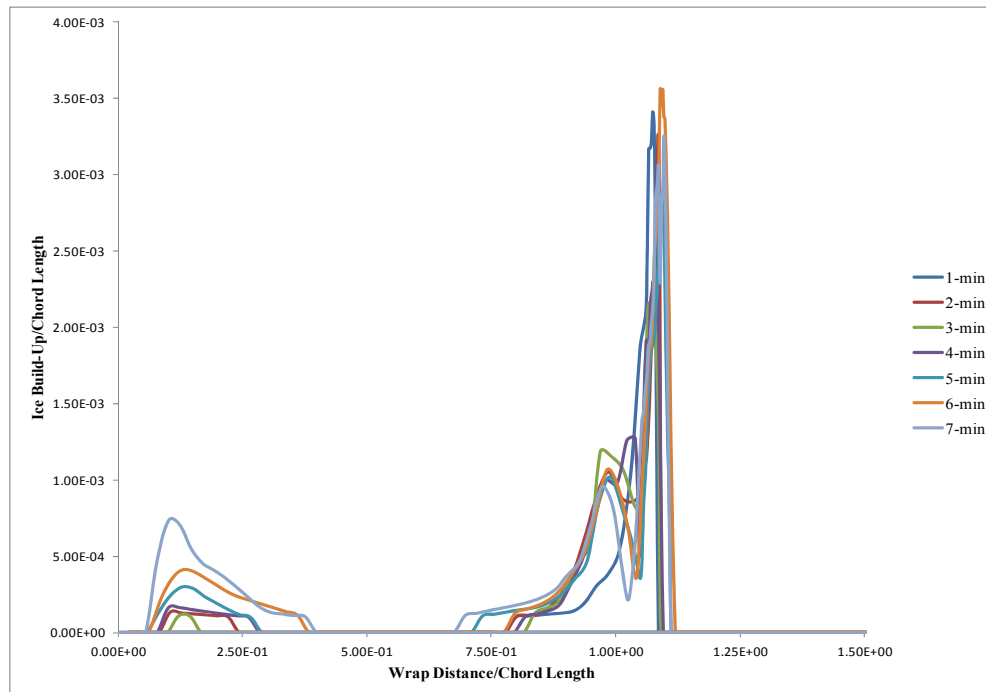


Figure 15: Ice Thickness for Time Variance at 0ft/Mach = 0.3135/455.67°R

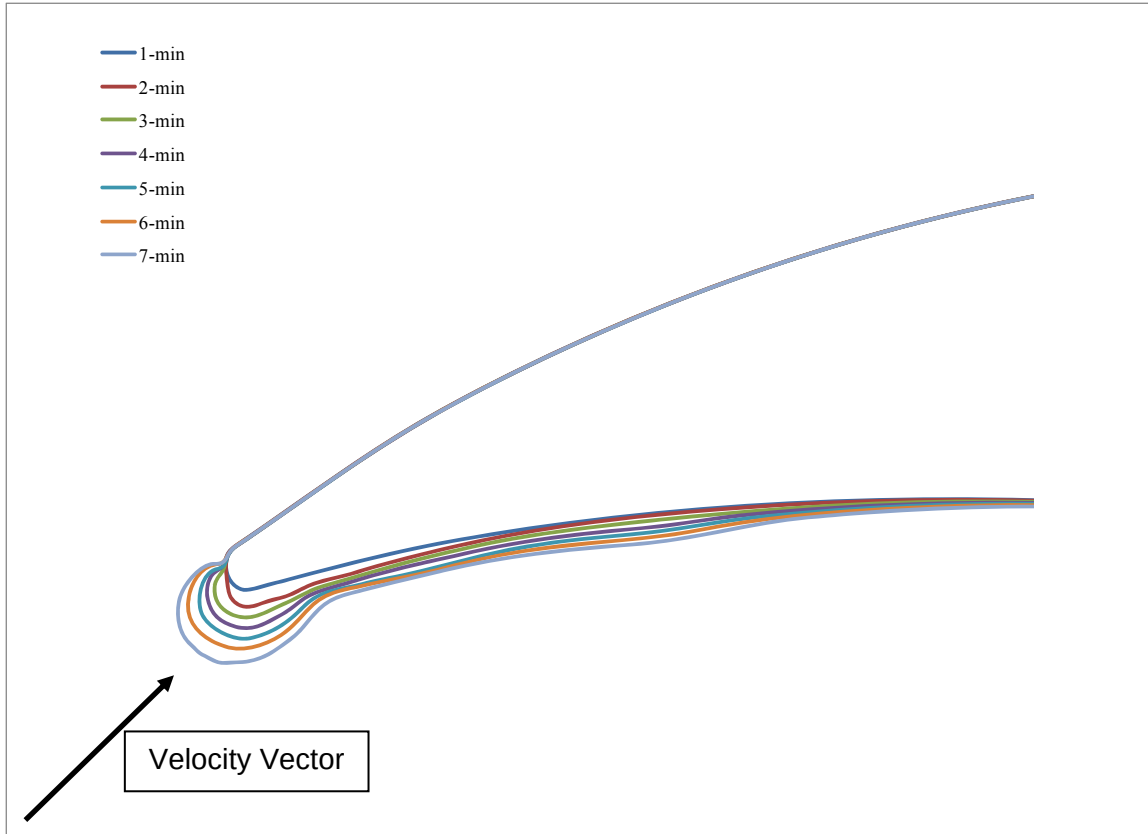


Figure 16: Ice Accretion for Time Variance at 0ft/Mach = 0.3135/455.67°R

Figure 16 shows that for this particular flight condition (0ft/Mach=0.3135/455.67°R) only rime icing occurs. This confirms that rime ice occurs primarily at lower temperatures since most of the droplets freeze on impact and do not melt and run down the surface of blade. It is also shown that the ice thickness increases almost 80% between 4 and 7 minutes indicating that any action to stop or reduce the accumulation must happen quickly. The time ranges were chosen to generate a trend and remain within the requirements laid out in JAR/FAR 25.1419 Appendix C [21] and EAS CS-E Amendment 3 [22].

Figure 17 and Figure 18 show that after 7 minutes of ice accretion, separation and more un-steady flow begin to occur. This is typical behavior that can be seen in all flight conditions and occurs due to the low air velocity and recirculation behind the ice.

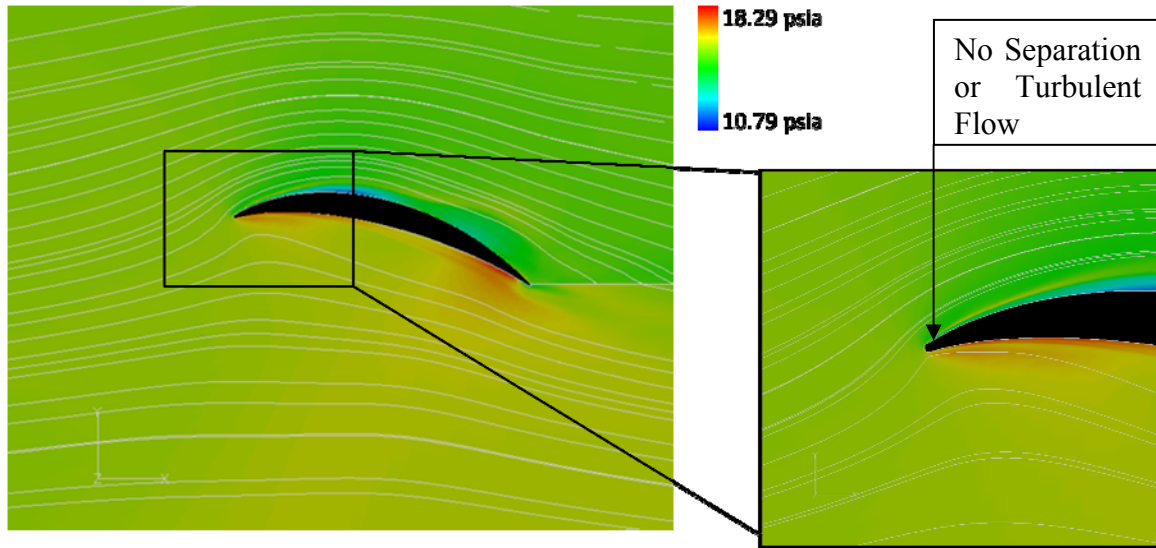


Figure 17: Clean Blade Flow Visualization

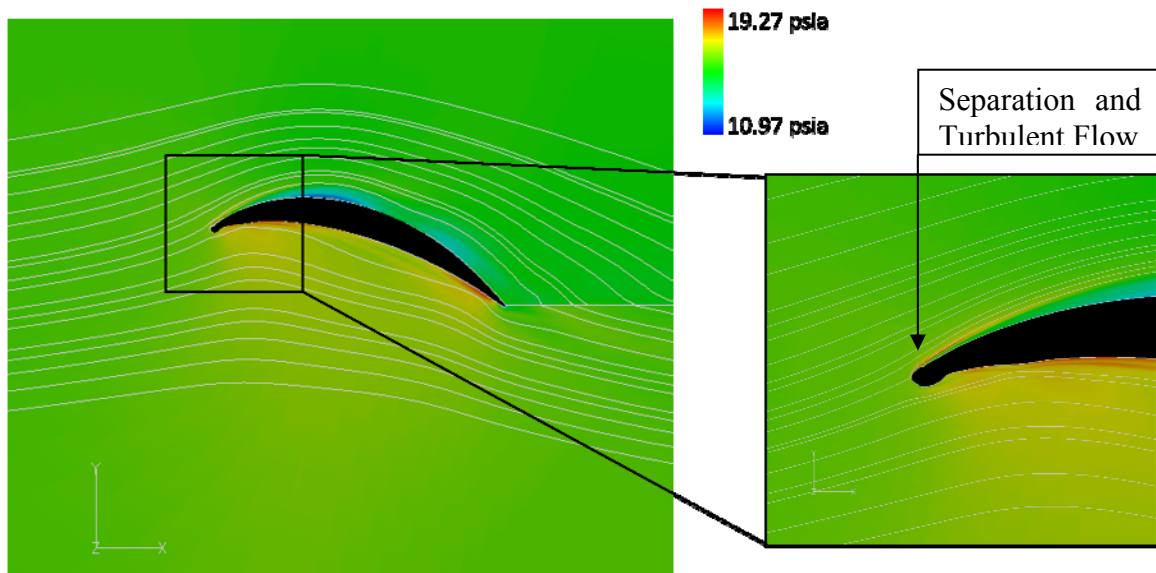


Figure 18: Iced Blade Flow Visualization

Throughout this thesis several flight conditions were analyzed in order to ensure the best understanding of the ice ingestion issues. The figures shown below (Figure 19 and Figure 20) demonstrate the importance of an investigation across the flight and icing envelope since different types of ice can accumulate over certain times for different flight conditions. One important aspect of the build-up in Figure 19 and Figure 20 was the formation of glaze ice developing on the blade during the last 2 minutes of the simulation (shown as a double horn ice shape). This phenomena was caused by the droplets not freezing on impact and running down the surface of the blade before freezing. Further analysis concerning the variations in the flight conditions and the subsequent effects on the ice accretion are shown in later sections of this thesis.

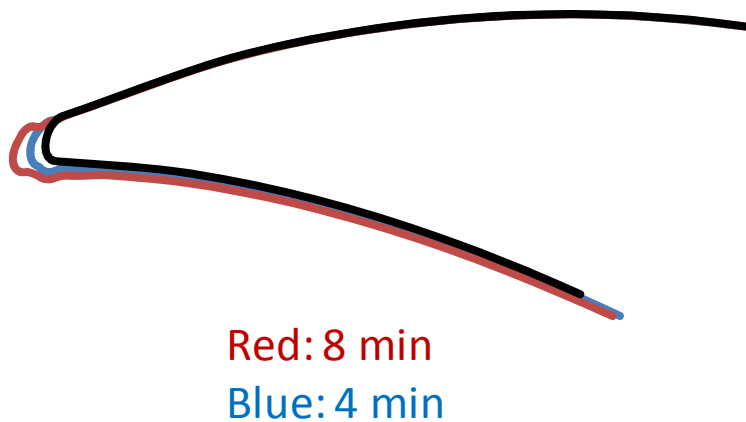


Figure 19: Ice Accretion for 0ft/Mach = 0.3059/478.67°R

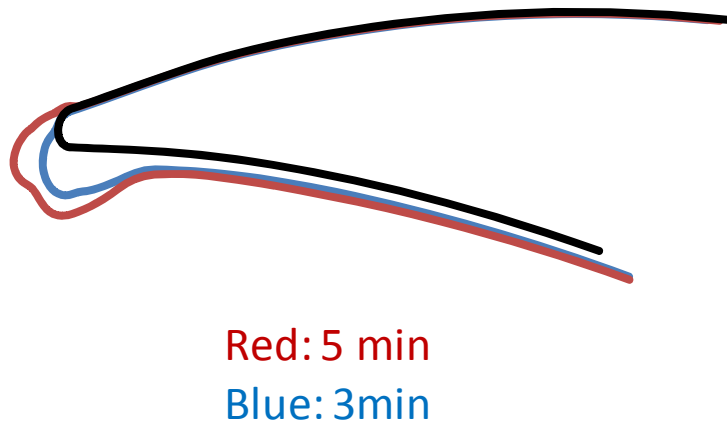


Figure 20: Ice Accretion for 10ft/Mach = 0.3135/455.67°R

By showing this variance in time for the different flight conditions, it can be seen that flight condition has a very large impact on the type, size, and shape of the ice on a blade. Also the time variance shows the importance of having an anti-ice system on the front stages of a compressor. If one is not present, ice can build up very fast and cause an increase in the possibility for a compressor stall or failure if not corrected.

5.2 DROPLET SIZE VARIANCE

There are two primary icing conditions that can vary and change the ice shape and size. These are the droplet size and liquid water content. The first that will be varied is the droplet size. The flight conditions specified determine the effects of droplet size were 0k/Mach = 0.3135/455.67°R and 10k/Mach = 0.3135/455.67°R. The liquid water content (LWC) was also held at a constant 0.55 g/ m³ and 1.5 g/ m³ for the sea level and 10k-ft,

respectively. Figure 21 shows how changing the droplet size from $20\mu\text{m}$ to $50\mu\text{m}$ (chosen from past research data and certification requirements) after 7 minutes.

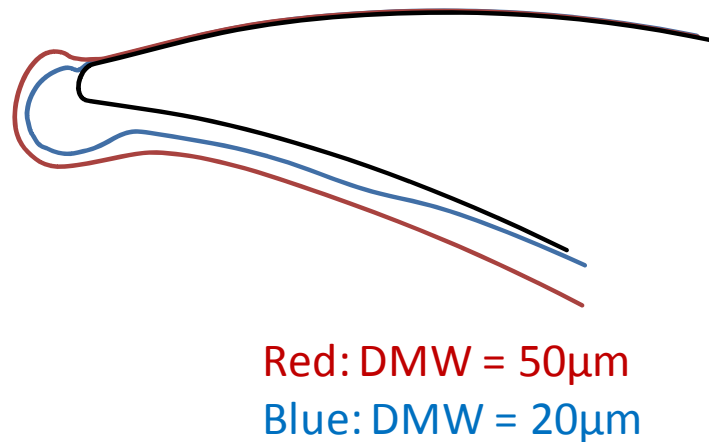


Figure 21: Effect of DMW Variance on Ice Shape at 0k-ft

Figure 22 shows that in addition to the larger horn length for the larger droplet size (approximately 15% larger), ice accretes along the entire blade at a much higher rate. This indicates that not only is there the risk of the horn shedding, which occurs once force of the ice weight and air flow combined with the convective heat transfer become too large for the bonds with previous layers, but the entire blade has changed characteristics dramatically for this large droplet size. With effectively a change in blade geometry, the chance of a stall increases greatly since the blade is no longer operating as designed.

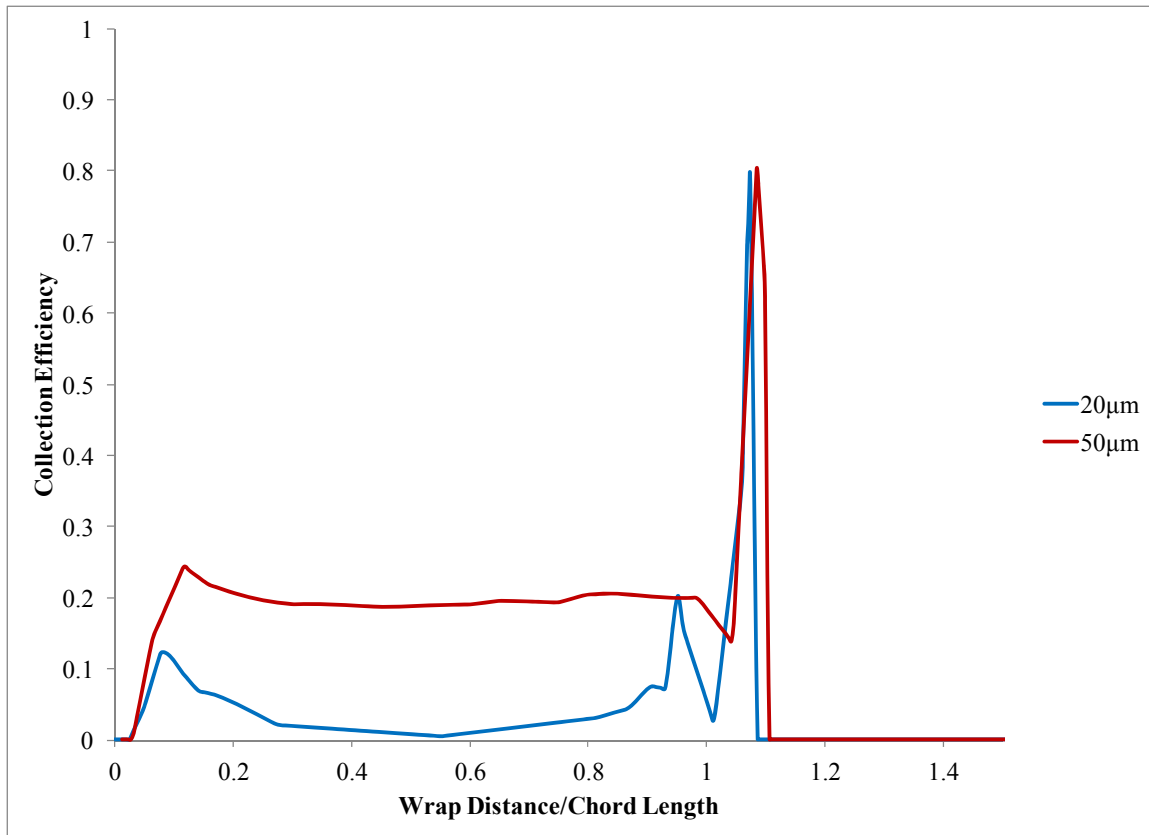


Figure 22: Collection Efficiency for DMW Variance at 0k-ft

A second flight condition was considered when analyzing the effects of droplet size. The change in flight condition consisted of a high altitude (10k-ft) and higher liquid water content (1.5 g/m^3). This flight condition illustrated that similar effects will occur across the flight and icing envelope. Figure 23 shows the droplet size variation for 10k-ft/Mach = 0.3135/455.67°R.

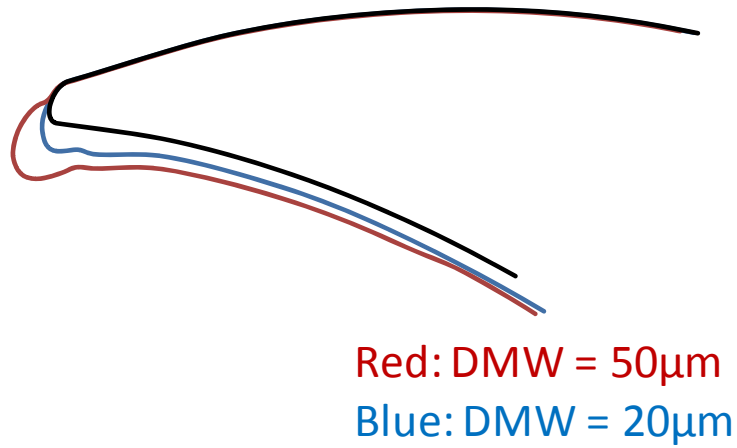


Figure 23: Effect of MVD Variance on Ice Shape at 10k-ft

Figure 24 shows a similar trend in the collection efficiency for the entire blade as the sea level condition; however, the 20 μ m droplet size shows more build-up at 10k-ft than at sea level. This difference is a result of the altitude variance that is to be discussed later.

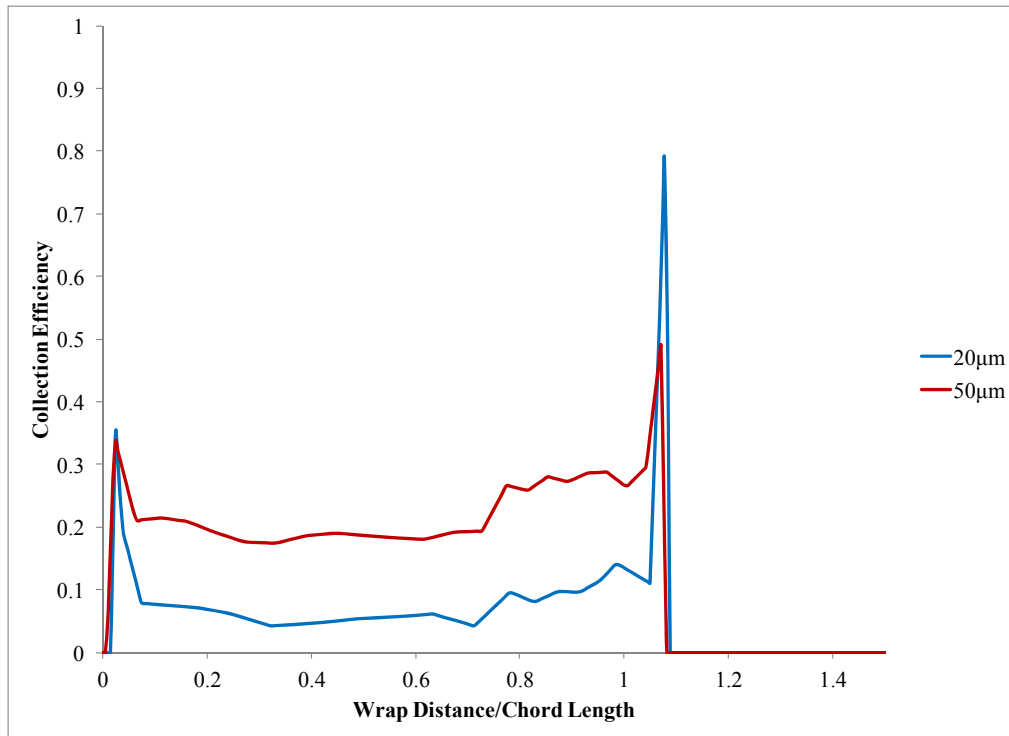
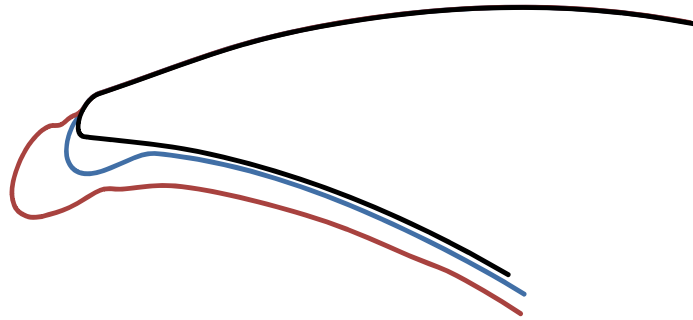


Figure 24: Collection Efficiency for DMW Variance at 10k-ft

5.3 LIQUID WATER CONTENT VARIANCE

The second icing condition that was varied is the liquid water content. The liquid water content is the measure of the amount of water in a specific volume of cloud. The flight condition for the analysis will be at 10k-ft with a droplet size of 20μm. The ice accretion process was only run for 2 minutes since significant ice will accumulate much faster for this higher LWC than for the smaller values previously shown. While the accretion process was run for a significantly smaller amount of time, it still falls within the EASA requirements. Figure 25 shows that for the higher LWC, a horn length of approximately 1.75 times as large will develop. Further analysis showed that it would

take 5 minutes for the LWC of 0.55 g/m^3 to reach the horn length of the higher LWC (1.5 g/m^3) at 2 minutes.



Red: LWC = 1.5 g/m^3

Blue: LWC = 0.55 g/m^3

Figure 25: Effect of LWC Variance on Ice Shape at 10k-ft

An interesting aspect of analyzing the collection efficiency was where the beginning of ice accretion for the blade occurs. In the case for the lower LWC at 2 minutes, a large spike in the collection efficiency can be seen (Figure 26). This spike shows where the beginning of the ice shape began. It occurred further towards the leading edge than for the higher LWC indicating ice accumulation across the whole blade was less along with the smaller horn length. While the larger horn length decreases the performance by increasing the mass flow blockage, the new blade shape (due to icing build-up on entire blade) also decreases performance by changing the pressure profile on the blade.

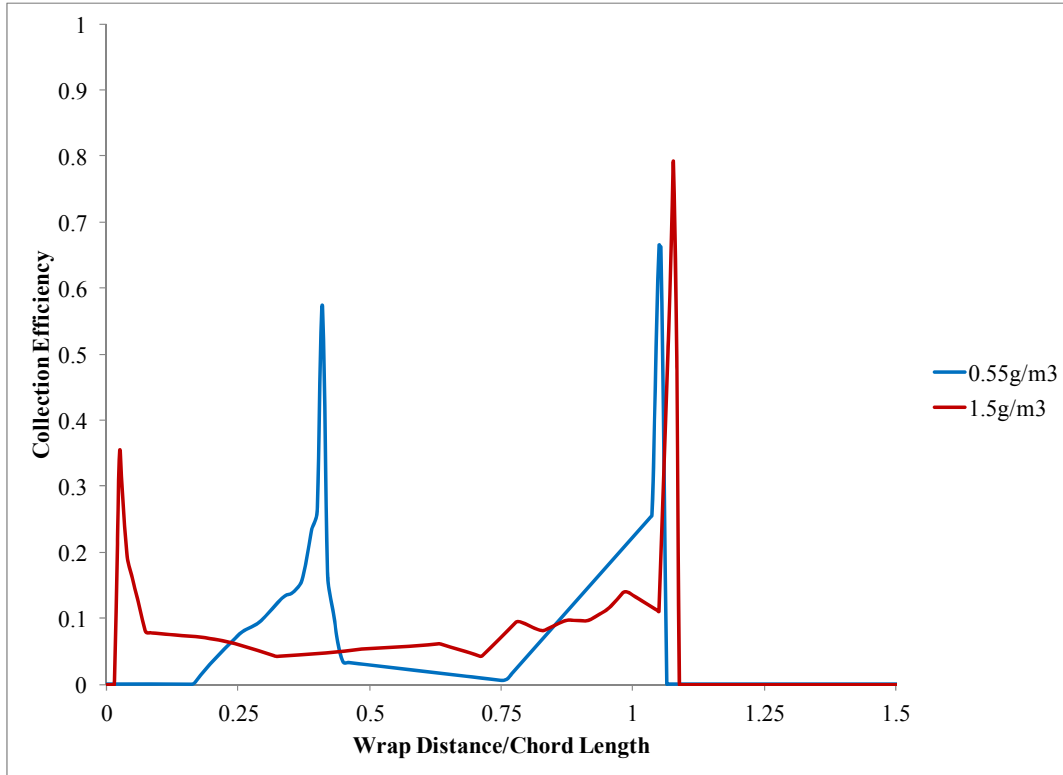


Figure 26: Collection Efficiency for LWC Variance at 10k-ft

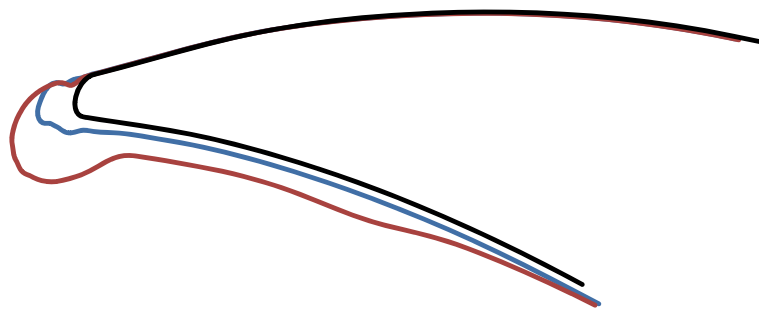
5.4 TEMPERATURE VARIANCE

The first flight condition change to be analyzed was the freestream temperature around the blade. By changing the freestream temperature, the speed of sound changes (shown in Equation 10) and causes the Mach number to be changed (Equation 11).

$$a = \sqrt{\gamma RT} \quad (10)$$

$$M = \frac{V}{a} \quad (11)$$

Figure 27 shows that for the higher temperature, the ice build-up on the blade is less than half the ice build-up on the blade at the lower temperature. Also the higher temperature indicates that glaze ice was beginning to form on the blade.



Red: $T = -4^{\circ}\text{F}$

Blue: $T = 19^{\circ}\text{F}$

Figure 27: Effect of Temperature Variance on Ice Shape at 0k-ft

The smaller horn length is due to the runoff and evaporation for more water droplets during the impingement process. This causes the liquid water to simply run down the length of the blade without causing any significant performance loss. While the colder temperature contributes to a more rapid build-up and a larger amount of ice, only rime ice forms for this case. The higher temperature caused glaze ice to form due to the rundown from the stagnation point. This can be seen by the multiple horns beginning to form. This double horn can also be seen in the collection efficiency in Figure 28. This double horn is shown as a double spike in the efficiency data.

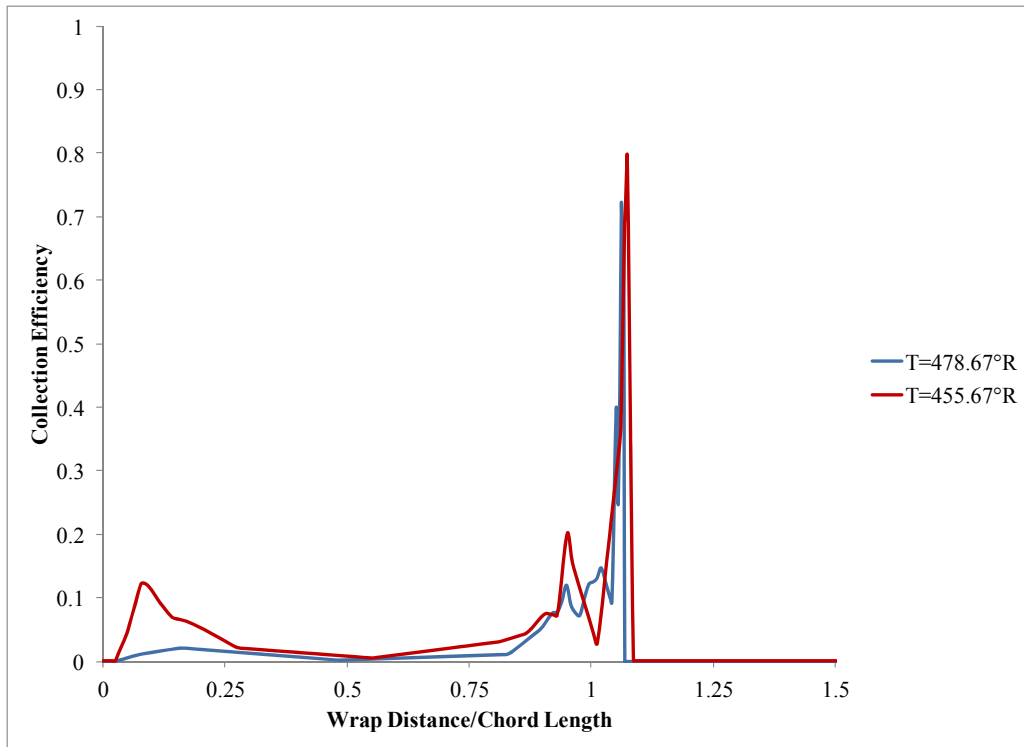
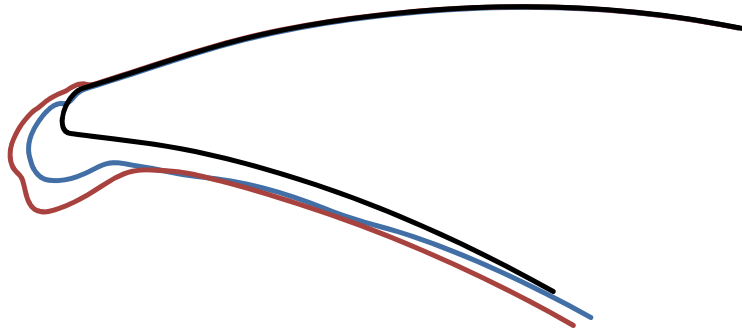


Figure 28: Collection Efficiency for LWC Variance at 10k-ft

5.5 ALTITUDE VARIANCE

The final flight condition that was varied was altitude. The change in altitude did not prove to have a significant effect (shown in Bartlett [23]). However, during an actual flight a temperature change is associated with changing altitude. This temperature change coupled with the altitude does cause notable changes in the size and shape that needed to be analyzed (a horn length approximately 40% larger at the higher altitude). With a higher altitude and lower temperature, ice accretion increases for two reasons: the evaporation characteristics of the water change (varies the freezing fraction) and the Reynolds number on the blade varies, which causes the convective heat transfer to change. Also glaze ice begins to form after 5 minutes (Figure 29) at the higher altitudes.



Red: Alt = 10k
Blue: Alt = 0k

Figure 29: Effect of Altitude Variance on Ice Shape

The smaller build-up of ice on the blade was primarily caused by the higher heat transfer across the blade at sea level. While at higher altitudes, the lower pressure allows for greater evaporation and a lower freezing fraction, which is the ratio of interacting particles to the particles that freeze on the blade. However, with the increased evaporation, the kinetic energy due to impingement decreases. This decrease in kinetic energy as well as the decrease in the convective heat allows for a greater build-up of ice at higher altitudes. The freezing fraction calculation is shown in Equation 12.

$$N_f = \frac{T_{mp} + \Delta T_r - T_s}{\Delta T_r} \quad (12)$$

Also the collection efficiency (Figure 30) increases across the entire blade causing greater performance loss at the higher altitudes.

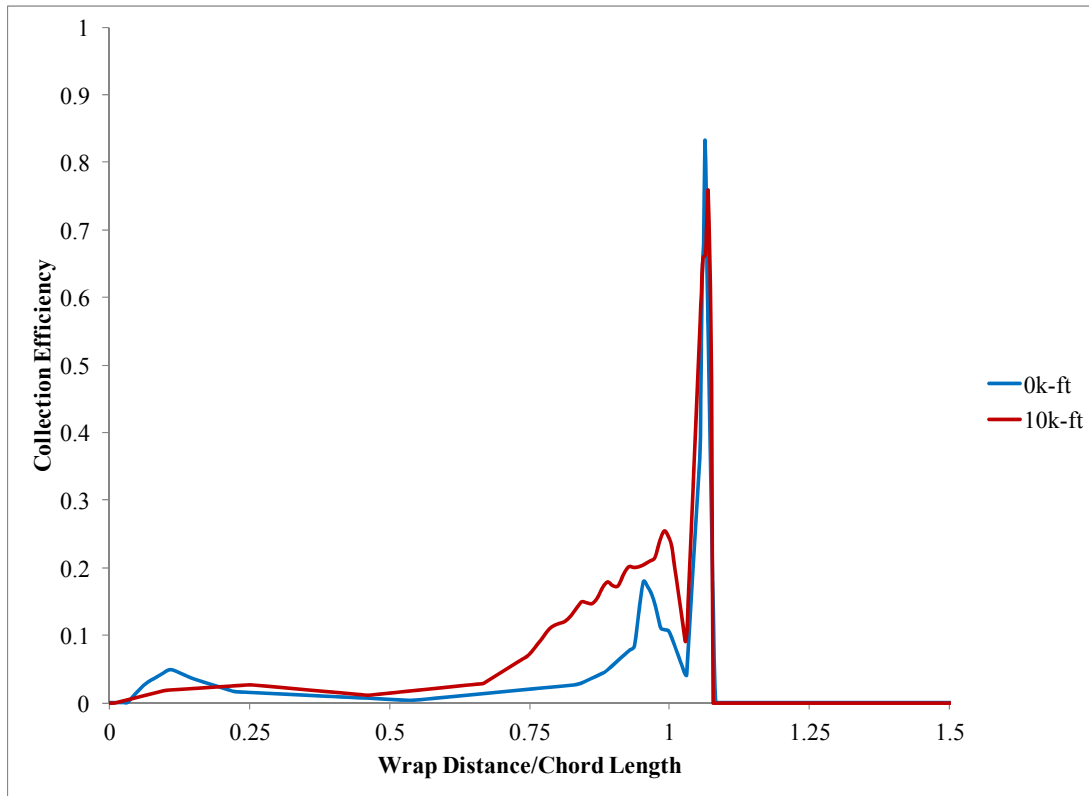
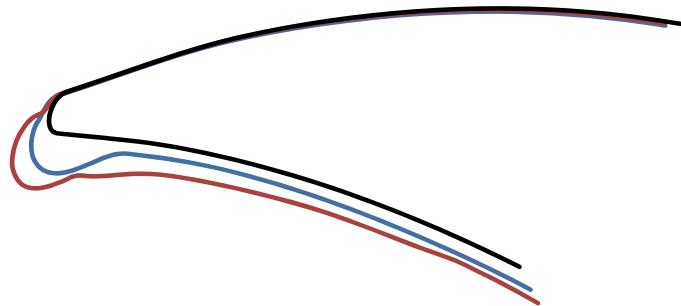


Figure 30: Collection Efficiency for Altitude Variance

5.6 LWC AND DMW VARIANCE

The last variation to analyze is the combination of the icing condition effect on accumulation. It was shown that the larger droplet size and liquid water content cause a greater ice shape. Therefore, Figure 31 further confirms that even after only 2 minutes of running at 10k-ft the larger DMW and larger LWC have a more significant effect on the accumulation process.



Red: DMW = $50\mu\text{m}$, LWC = $1.5\text{g}/\text{m}^3$

Blue: DMW = $20\mu\text{m}$, LWC = $0.55\text{g}/\text{m}^3$

Figure 31: Effect of DMW and LWC Variance on Ice Shape, 10k-ft/Mach =0.3135/455.67

From Figure 32, it is seen that for the smaller droplet size and liquid water content, the beginning of the ice shape on the blade begins further along the pressure side of the blade. Also ice accumulation occurred less along the whole blade in addition to the horn being smaller.

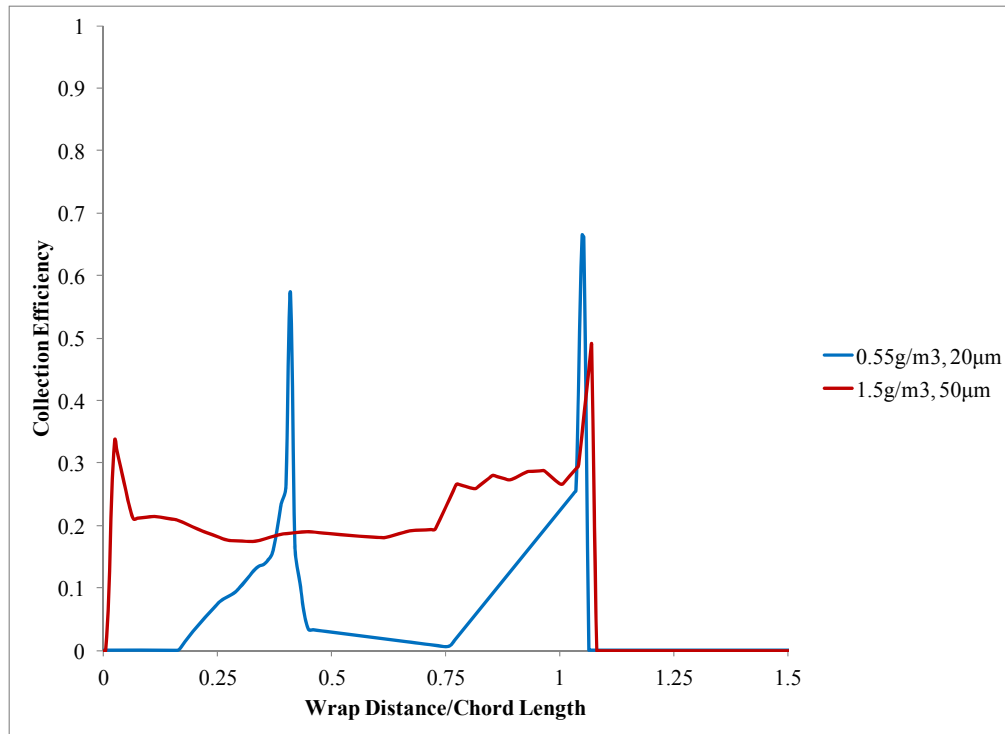


Figure 32: Collection Efficiency of DMW and LWC Variance

5.7 PERFORMANCE LOSS

The performance loss of a blade after ice accretion occurs was determined by calculating the pressure and mass flow losses across the blade. Figure 33 and Figure 34 show a typical performance relationship between the ice thickness and these loss terms.

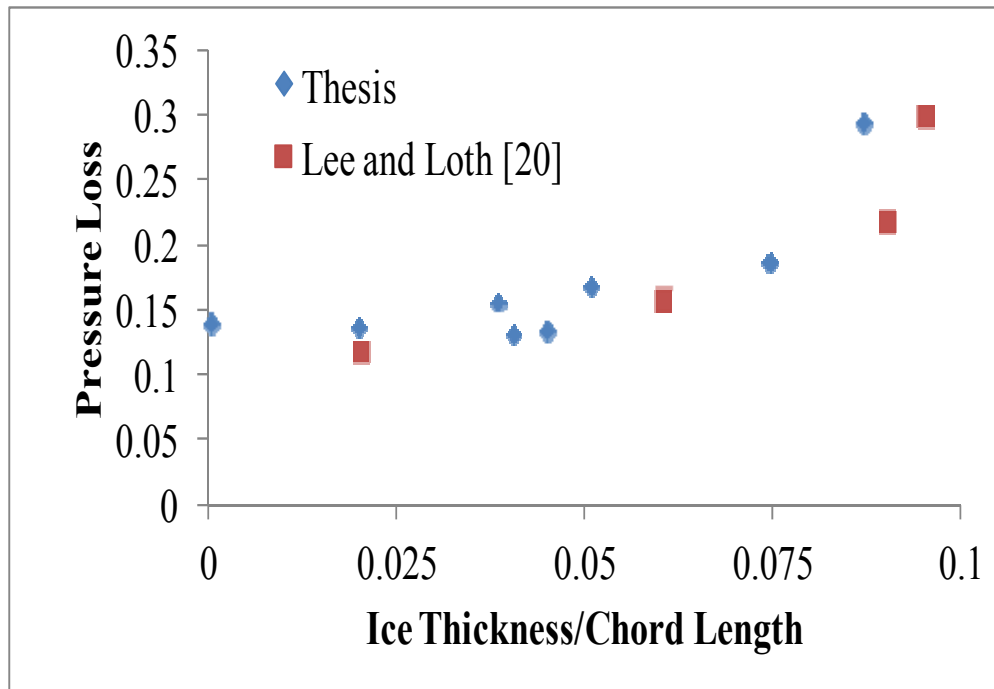


Figure 33: Pressure Loss vs. Ice Thickness at 0k-ft

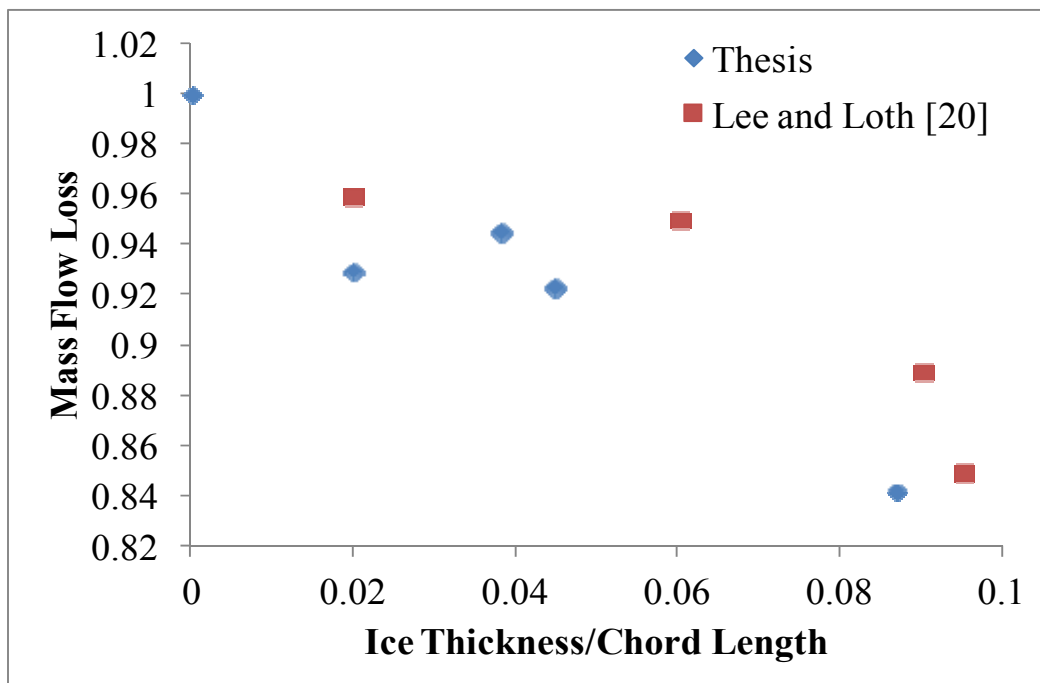


Figure 34: Mass Flow Loss vs. Ice Thickness at 0k-ft

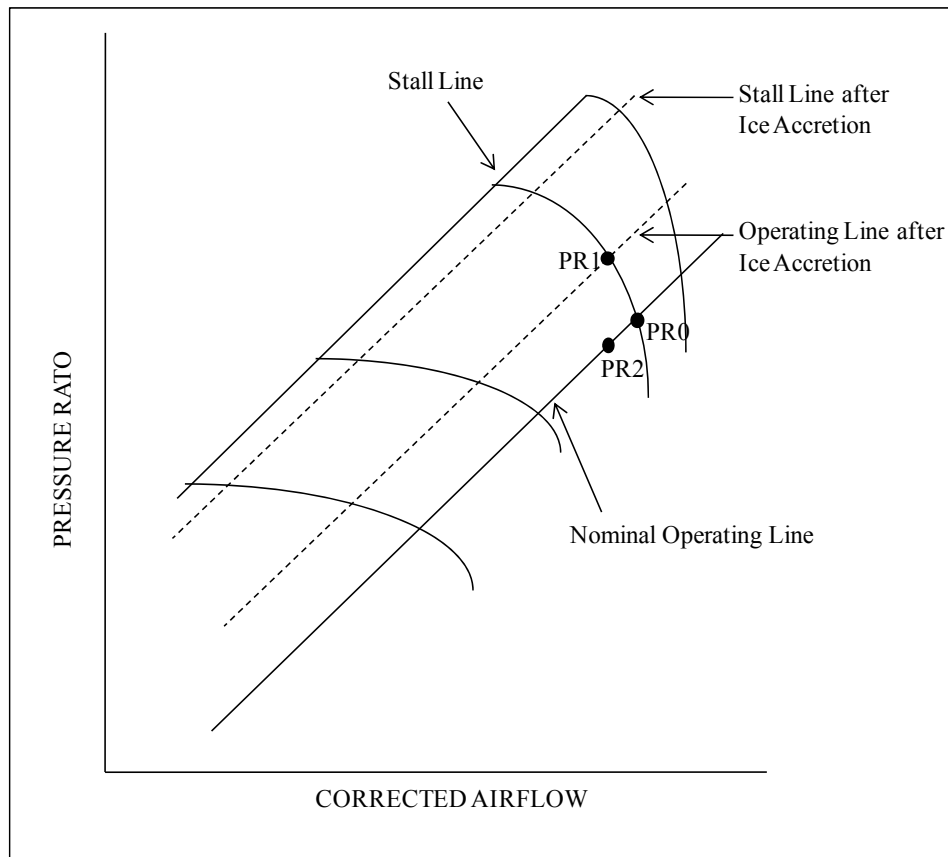


Figure 35: Typical Compressor Map Showing Ice Accretion Effects

Figure 35 shows how a typical compressor operating line would be affected by the build-up of ice. It is shown that the operating line increases with the higher pressure rise through the compressor. With this increase in pressure ratio (PR1), the stall margin is reduced and risk to the engine increased. In order to prevent the engine from stalling, the control system will need to reduce the pressure ratio (PR2). To achieve this reduction in pressure ratio, engine speed is reduced, and with this reduction in speed, the mass flow is also reduced. In addition to this increase in the operating line, a decrease of the stall

line (or stability limit) occurs due to the increase of flow separation as ice accretes on the blade.

The results confirm that for an increasing horn length and ice accretion along the blade, the performance will decrease. This decrease in performance is due to the increases in the loading of the blades, blockage, turbulence, and a reduction in the stall margin. Since the figures shown above show the overall trend and agree well with past research, the coupled code can now be executed across the engine or stage envelope in order to determine where problem areas are likely to arise.

6. SUMMARY & CONCLUSIONS

A number of available computer software codes were combined to develop an analysis capability to accurately assess blade performance due to ice accretion. This package used a 2-D computational fluid dynamics approach by solving the Navier-Stokes equations for the changes in geometry due to the ice accumulation over time. Previous techniques to determine the effect of icing on a turbine engine involve using potential flow solvers or accepting the risk and cost of performing ground and flight testing. Neither of these methods result in a full or accurate understanding of what kind of performance loss would occur and lead to a stall or flameout event.

In order to be able to use the CFD method, the first step was to generate a grid for the complex geometry. The CFD simulation required the use of a 2D grid, and the initial grid (generated with ICEG2D) was constructed around an airfoil with no ice accumulation.. This newly created grid was then fed into the Navier-Stokes flow solver, WIND, to calculate the flow around the blade and determine the performance of the blade. By using WIND instead of a potential flow solution, the solution increased in accuracy and the coupled code accounted for turbulence and boundary layer conditions. Once the clean flow solution was determined, the ice accretion software (LEWICE) was executed to determine the amount and position of ice on the blade. Once this new geometry was determined, it was fed back into the grid generation software, and the process of grid generation and blade performance was repeated for the desired number of iterations and times.

The cases executed in this thesis to validate the coupling of the code and determine the icing effects on the performance of a turbine stage were all based on past research data and the AGARD report [3]. All cases were run on the blade 67A stator design, which is used for a majority of the research for ice accretion.

The first step in determining the effects of icing was to vary the flight and icing conditions to find the conditions that cause the most profound changes in blade geometry. The conditions that were varied were time, freestream temperature and pressure, liquid water content, droplet size, and the combination of liquid water content and droplet size. Also by changing some or all of these parameters, the shape, size, and type of icing will vary. With each different type of ice accumulation, the performance of the blade also varies. The analysis in this thesis addressed these issues.

The conditions that had the largest impact were the liquid water content and the freestream temperature. By raising the liquid water content, a horn length can be created after 2 minutes that is nearly 2-3 times as large as one after the same amount of time with lower liquid water content. It was also shown that it would take nearly 3 times as long to reach the same horn length for the lower LWC. This means that for an engine going through a cloud with a large LWC, the pilot has very little time to turn on an anti-icing system or get out of the cloud before large adverse effects occur to the engine.

The other condition with the largest effect was the freestream temperature. With greater temperature, glaze ice is more likely to occur due to the majority of particles running down the length of the blade without freezing. The high energy of the particles

caused the majority of the water to flow down the blade without causing any negative effects. The particles that do freeze on the surface began to form glaze ice, which can be seen as the double horn shape. These horns formed around the stagnation point, where the heat transfer is the greatest and most of the melting and evaporation occur.

Once the flight condition variation effects on ice accretion were determined, the performance loss due to the build-up was analyzed. The performance loss was determined using two different methods, the pressure loss across the blade and the mass flow loss due to the change in geometry. It was shown that for the increasing horn length, the performance loss increased dramatically after the ice thickness to chord length ratio reached approximately 0.08. This means that the likelihood of a blade or stage failure once the ice accumulates to a thickness greater than 8% of the chord is very large and requires immediate action from the pilot.

7. RECOMMENDATIONS

This thesis analyzed the process in which the performance loss due to ice accumulation should be conducted in order to save time, money, and improve safety. Even though the data shown is for a given blade a certain pressure loss can occur. Much more simulation and test cell analysis across the entire flight and icing envelope would further ensure the validity of the technique and codes used.

A final recommendation would be to apply the method and coupled codes in this thesis to analyze much more complex systems. These complex systems could include multi-element blades, cascades of blades, transient effects, full compression systems (including rotors), the addition of an anti-ice system, or 3D CFD applications. By studying these types of systems, more validity will be added to the code since it will be very similar to that of an actual engine test on a stand or during flight.

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APPENDIX

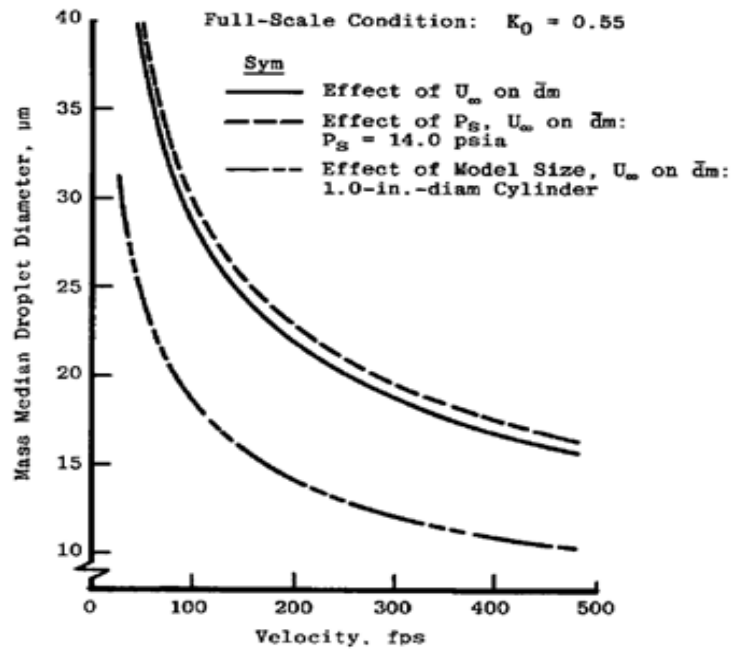


Figure A - 1: Effects on Droplet Diameter with Constant K_0 from Ruff [1]

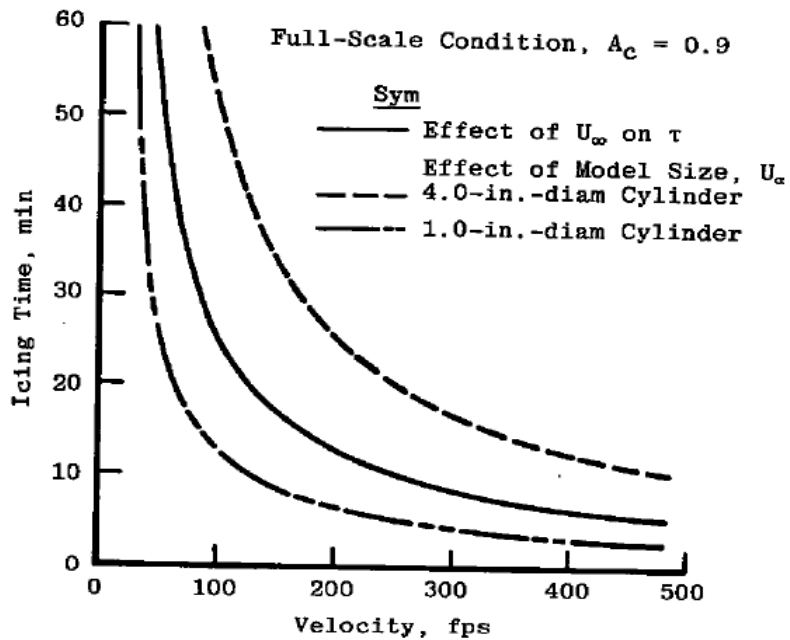


Figure A - 2: Effects of Icing Time with Constant A_c from Ruff [1]

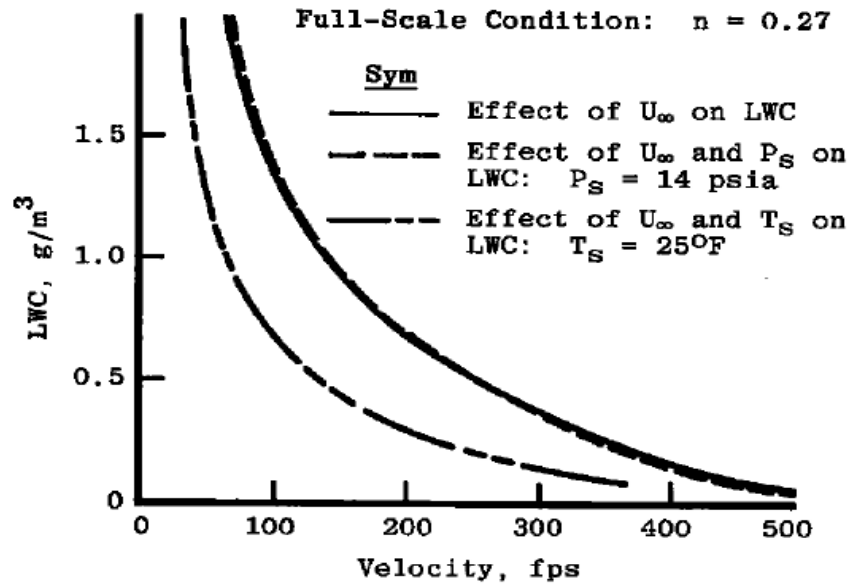


Figure A - 3: Effects on LWC with Constant N from Ruff [1]

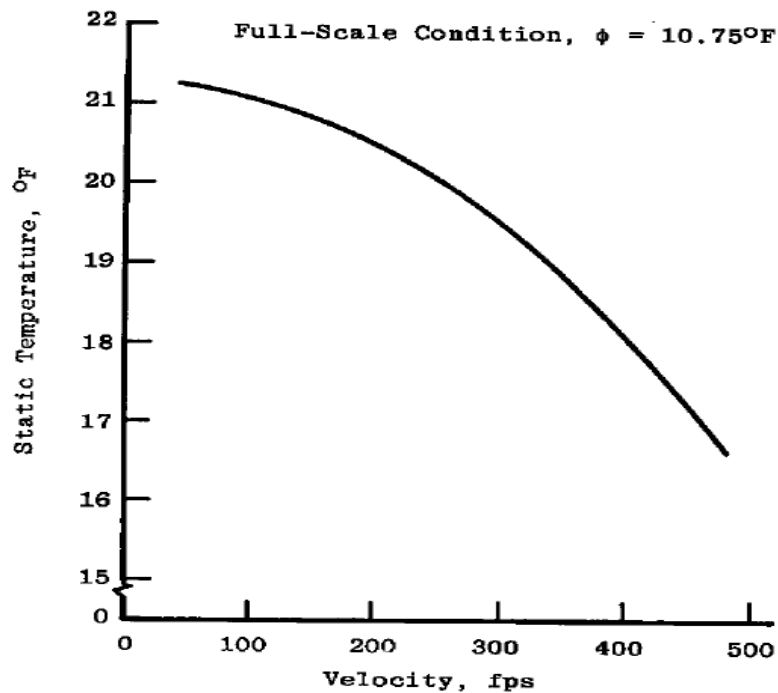


Figure A - 4: Effects on Static Temperature with Constant Φ from Ruff [1]

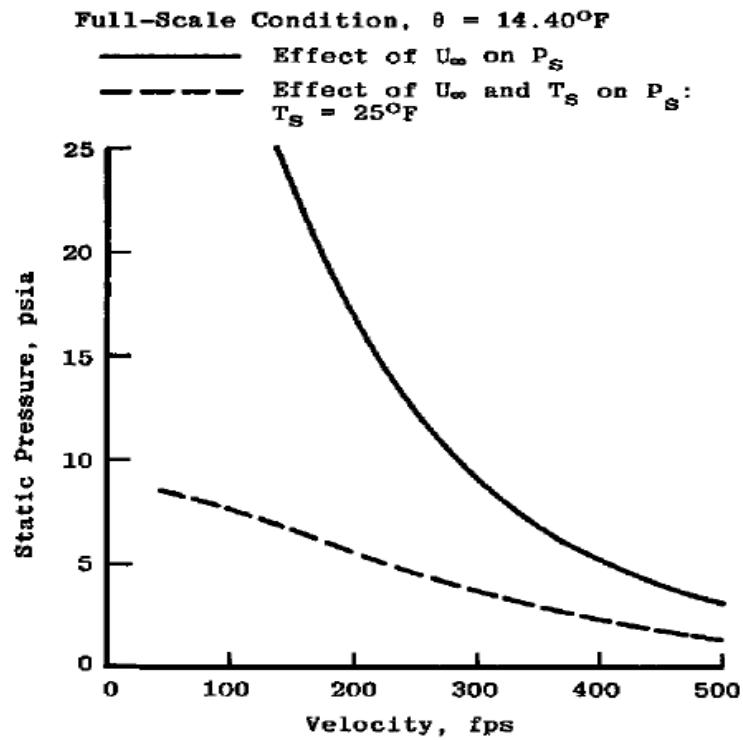


Figure A - 5: Effects on Static Pressure with Constant Θ from Ruff [1]

VITA

Rick Thomas Hutchings was born in Centralia, IL on June 6, 1985 to Mr. Thomas Hutchings and Mrs. Diane Hutchings. He attended Central City Grade School and Centralia High School in his hometown of Centralia, IL. In 2003, he graduated from High School and entered Embry-Riddle Aeronautical University in Daytona Beach, FL. In Aug. 2005, he entered Purdue University in West Lafayette, IN and in May 2007 received his Bachelors of Science degree in Aeronautical and Astronautical Engineering. During his time at Purdue University, he spent a summer working as an intern for the Aerospace Testing Alliance at Arnold AFB. After graduation, he started working full-time for Aerospace Testing Alliance as a data analysis engineer in the Turbine Engine Testing department. He also enrolled in the graduate program at the University of Tennessee Space Institute in the spring of 2008.