Computational Fluid Dynamics-Icing: a Predictive Tool for In-Flight Icing Risk Management

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Abstract

In-flight icing is a hazard that continues to afflict the aviation industry, despite all the research and efforts to mitigate the risks. The recurrence of these types of accidents has given renewed impetus to the development of advanced analytical predictive tools to study both the accretion of ice on aircraft components in flight, and the aerodynamic consequences of such ice accumulations. In this work, an in-depth analysis of the occurrence of in-flight icing accidents and incidents was conducted to identify high-risk flight conditions. To investigate these conditions more thoroughly, a computational fluid dynamics model of a representative airfoil was developed to recreate experiments from the icing wind tunnel that occurred in controlled flight conditions. The ice accumulations and resulting aerodynamic performance degradations of the airfoil were computed for a range or pitch angles and flight speeds. These simulations revealed substantial performance losses such as reduced maximum lift, and decreased stall angle. From these results, an icing hazard analysis tool was developed, using risk management principles, to evaluate the dangers of in-flight icing for a specific aircraft based on the atmospheric conditions it is expected to encounter, as well as the effectiveness of aircraft certification procedures. This method is then demonstrated through the simulation of in-flight icing scenarios based on real flight data from accidents and incidents. The risk management methodology is applied to the results of the simulations and the predicted performance degradation is compared to recorded aircraft performance characteristics at the time of the occurrence. The aircraft performance predictions and resulting risk assessment are found to correspond strongly to the pilot's comments as well as to the severity of the incident.

Résumé

Le givrage en cours de vol constitue un danger qui continue d'affliger l'industrie aéronautique. Ceci, malgré toute la recherche qui vise à atténuer les risques. La récidive de ce type d'accident donna un nouvel élan au développement d'outils analytiques de pointe dans ce domaine. Ces outils permettent d'étudier de manière préventive, l'accrétion de glace sur les composants de l'avion, ainsi que les conséquences aérodynamiques de telles accumulations. Le présent travail comprend une analyse approfondie de l'occurrence d'incidents liés au givrage en cours de vol dans le but d'identifier les conditions météorologiques problématiques. Pour en apprendre d'avantage, un modèle représentatif d'une aile d'avion à haut risque fut développé. Les conditions d'opérations de cette aile furent simulées par un logiciel d'analyse de dynamique des fluides afin de recréer les résultats de simulations menées en soufflerie givrante. La quantité d'accumulation de glace ainsi que la dégradation des performances aérodynamiques sont calculées pour une gamme de vitesse et d'angles de tangage. Ces simulations démontrent une perte importante de la portance maximale de l'aile ainsi qu'une réduction de l'angle de décrochage. À partir de ces résultats, une méthodologie d'analyse de risques fut développée, selon les principes de gestion de sureté. Le but d'une telle analyse est d'évaluer le niveau de danger associé au givrage en vol pour un appareil précis selon des conditions de vol déterminées avant le décollage. De plus, cette méthodologie servira à évaluer l'efficacité du système de dégivrage, ainsi que le protocole de certification d'un appareil qui opère dans des conditions propice au givrage en vol. Le fonctionnement du système de gestion de sécurité est ensuite démontré à l'aide de simulations d'accidents liés au givrage en cours de vol selon les informations obtenues dans le rapport d'incident. La méthodologie fut ensuite appliquée aux résultats des simulations; les pertes de performance, calculées par le logiciel d'analyse de dynamique des fluides, furent comparées à la performance et au comportement de l'aéronef tel qu'enregistré au moment de l'accident. Les résultats démontrent que le système de gestion de risque développé dans cet ouvrage peut prédire de façon précise, avec l'information disponible uniquement avant le décollage, la sévérité du givrage en vol pour un avion spécifique.

1. Introduction

Since the early days of manned flight, pioneer aviators have had great respect for the powers of nature, and were wary of flying in unfavorable conditions. “The pilot required good visibility for safe takeoff; attitude control; navigation; terrain collision avoidance; avoidance of areas with adverse meteorological conditions such as icing and heavy turbulence; […]; as well as for approach and landing.”[1] There is no doubt that technological improvements have evolved aviation into the safest means of transportation in the world[2], yet incidents and accidents related to in-flight airframe icing still occur.

These occurrences have given renewed impetus to the development of analytically predictive tools to study both the accretion of ice on aircraft components in flight, and the aerodynamic consequences of such ice accumulations. Studies presented by Green [3] and by Petty [4] regarding in-flight icing accidents and incidents, have revealed that some commercial, as well as general aviation aircraft, could encounter conditions where the current ice protection systems fail to ensure the safe operation of the aircraft, given the pilots’ workload in the cockpit and the lack of reliable advance warning mechanisms. The October 31, 1994 ATR-72 accident in Roselawn, Indiana, resulting in 68 fatalities[5], initiated much of the effort directed toward preventing future icing accidents. Yet, 17 years later, similar accidents continue to occur. Most recently, in-flight icing was found to be a major contributing factor in the crash of an ATR-72 in Cuba on November 4th, 2010. It is imperative to maintain these research efforts and to continue to strive for the goal of zero accidents. The present research explores predictive technologies such as computational fluid dynamics (CFD) icing simulations (here through FENSAP-ICE[6]) and applies the information gleaned from these analytical tools to the development of a comprehensive, aircraft specific risk assessment tool for in-flight icing.

CFD has become a widely accepted tool in the design and optimization of aircraft; and should be considered for a more important role in the icing certification and safety management process to pinpoint the most critical meteorological conditions and flight phases that, in combination, present the greatest risk to a particular aircraft. Since not all certification conditions can be tunnel-tested, flight tested nor encountered in natural icing testing; only the additional use of analytical methods can make it possible to safely explore, even if only qualitatively, the entire icing envelope [7]. This study describes how CFD analysis can be used in conjunction with meteorological data to identify hazardous zones for a particular aircraft type. In addition, it demonstrates how the risk associated with in-flight icing for a specific aircraft can be better identified and managed through improved predictive information for certification and operations.

A initial overview of current literature on the topic of in-flight icing addresses three general areas: CFD applied to in-flight icing, the regulatory framework for in-flight icing, and works pertaining to the evaluation of aerodynamic properties of a contaminated airfoil. This is followed by a summary of the phenomenon of in-flight icing and how it can impact aircraft performance. The industry's meteorological hazard mitigation strategy is reviewed, including a description of anti-icing and deicing techniques, as well as an examination of the current in-flight icing regulations that are applicable to the United States.

To gain a better understanding of the scope of the in-flight icing problem, a spatial analysis of accidents and incidents is performed, thus identifying regions that have a higher number of occurrences, and climates that are more conducive to icing events. Through superposition of several layers of meteorological information and accident data on the world map, one can make rapid visual correlations between accident occurrences, geographic location, and meteorological conditions. This analysis qualifies the global state of in-flight icing accidents and guides the remainder of the efforts in this study to improve the risk management strategy for in-flight icing hazards.

The analytical methods used to study in-flight icing scenarios require a numerical wind tunnel in which the geometry of the airfoil and the operating conditions can be simulated. Creating a versatile grid is necessary for the efficient and accurate simulation of different flight conditions.

Simulations are run using the FENSAP-ICE system and the results are compared with experimental results to validate the model. The initial simulation run is performed without any ice accretion to determine if the aerodynamic properties of the uncontaminated airfoil, which will be used as a reference point for future simulation, match the experimental values.

Next, simulations are performed to validate the FENSAP-ICE predicted ice shapes, as well as the aerodynamic properties, by comparing to the experimental results obtained by Broeren and Bragg in 2002 [8], and by the subsequent results from the U.S. Department of Transport's "Investigation of Performance of Pneumatic Deicing Boots, Surface Ice Detectors, and Scaling of Intercycle Ice" [9]. The agreement of these results supports FENSAP-ICE's ability to reliably predict aerodynamic properties of iced airfoils in experimental conditions.

A safety risk management methodology is developed to provide a consistent and coherent process to evaluate the effects of in-flight icing on the operational performance of a specific aircraft. The risk assessment process considers several performance metrics to evaluate the level of severity of an occurrence and uses the meteorological reports to determine the probability.

After showing that the simulations can accurately predict the accretion and performance degradation of the airfoil in experimental conditions, the focus shifts outside the controlled environment to recreate real flight operation events based on factual accident reports. The results are analyzed with the risk management system as a proof of concept and are compared to actual aircraft handling characteristics at the time of the incident as described by the pilot in the cockpit voice recorder transmissions.

2. Literature Review

A review of existing literature pertaining to the application of computational fluid dynamics to the problem of in-flight icing is conducted to set a foundation on which to build the present work. These papers give insight into the benefits as well as some of the drawbacks of using different CFD tools to achieve the desired simulations. Subsequently, a review of aerodynamics literature pertaining to in-flight icing is conducted to determine how the phenomenon occurs, and what has been done from an aerodynamics point of view to address this issue. Finally, a chronological analysis of the certification and regulation proceedings relevant to the subject at hand is conducted to determine if there are any deficiencies or inconsistencies.

2.1. Computational Fluid Dynamics Literature

In the paper entitled "*Design of Ice Protection System and Icing Certification Through the FENSAP-ICE System*" [10] the authors discuss how CFD can be used in certification to help determine the most critical ice accretion conditions, which can then be further investigated using conventional methods. In addition, the droplet impingement model can be used to determine the adequate coverage for ice protection equipment such as pneumatic de-icing boots. The paper describes the different modules of the FENSAP-ICE system and how they interact to deliver accurate ice accretion predictions and aerodynamic properties for a given simulation.

In "*Development of a Second Generation In-Flight Icing Simulation Code*" [6] the authors describe and compare the benefits offered by the FENSAP-ICE system to two-dimensional and quasi-3D in-flight ice accretion simulation codes. The paper further describes the methods for computing turbulence, namely the one-equation Spalart-Allmaras model, which has been augmented to include an extension for rough-wall evaluation. The ice accretion simulation is extremely sensitive to turbulent heat fluxes. This paper also indicates that for the ice accretion calculation, if the flow is assumed to be fully turbulent, the numerical results can over-predict the heat fluxes around the stagnation point. Additional sources of error are stated as mesh related inaccuracies during solution for which flow solution based mesh adaptation between successive icing simulations is suggested to reduce the magnitude of this error. Finally, there may exist inaccuracies in the collection efficiency caused by the lack of continuous updates of the flow solution.

In "*Advances in CFD for In-Flight Icing Simulation*"[11] Habashi explains the importance of CFD in aviation and the inherent advantages the technology such as the ability to simulate a wide variety of icing conditions in a closely controlled manner. He goes to mention that scaling results is unnecessary and finally, that CFD-Icing tools can help to harmonize the study of aerodynamics and icing. The approach to supercooled liquid droplets (SLD) is described, as are the simplifying assumptions made in the mathematical derivation of energy and momentum equations. One such assumption is that the droplets travel at the free stream velocity. The author notes that this assumption is violated when extending the model to include SLD. The primary violation is that due to the large mean volume diameter (>40 μm), SLD droplets are no longer arranged in a stable atmospheric stratification, and do not travel at the free stream velocity relative to the aircraft. Instead, it is suggested that they are better described as a droplet cloud falling at terminal velocity. Issues of droplet deformation and break-up are also addressed.

2.2. Aerodynamics Literature

The FAA's "*Investigations of Performance of Pneumatic Deicing Boots, Surface Ice Detectors, and Scaling of Intercycle Ice*" [9] has been conducted on the National Advisory Committee for Aeronautics (NACA) 23012 airfoil in the icing wind tunnel. The methodology used consists of allowing ice to accumulate for a specified amount of time on the clean leading edge of a scaled version of the NACA 23012. An important limitation of this wind tunnel, however, is that it can only operate at local atmospheric pressure, and thus operational conditions cannot be varied to re-create operational air pressure and density. Moreover, the icing tunnel tests were performed at a true airspeed of 170 knots, considerably faster than the operational speeds of many general aviation aircraft. The report also identifies the typical angle of attack for this airfoil in descent and holding at 0 and 4 degrees, respectively. The operation and arrangement of the de-icing boots are described, along with details about the cycle durations, which are 1 minute for intermittent maximum icing (higher liquid water content), and 3 minutes for continuous maximum icing conditions (lower liquid water content). It should be noted that the wind tunnel is not capable of adequately housing the entire chord length of the airfoil (6 ft) and therefore the team opted to use a smaller (3 ft), specially designed hybrid airfoil consisting of a truncated leading edge section of the full-scale airfoil and a flap at 20% chord. The hybrid airfoil was shown to adequately replicate the impingement limits of the full-scale airfoil. Next, this report discusses the results from a flight test performed on an EMB 120 with a simulated ice shape installed on the leading edge of the wing. The resulting aerodynamic performance degradation, as well as the operation of the stall warning system are described in detail.

Using the same method and wind tunnel as the previous study, the results presented in "*Effect of Residual and Intercycle Ice Accretions on Airfoil Performance*" [8] investigate how the roughness remaining on the leading edge of the airfoil after the de-icing boots are activated, affects the subsequent ice accretion. The de-icing boots are cycled 2-3 times, at which point the resulting ice shapes are said to tend toward a steady state. The aerodynamic performance degradation caused by these ice shapes is evaluated in the NASA Langley Low-Turbulence Pressure Tunnel (LTPT). This study finds that, while the de-icing boots were effective in removing ice, the performance penalties caused by the formation of ice in between boot cycles are substantial and that sand paper, which was used to simulate intercylce ice for certification, was not an adequate substitute to simulate intercycle ice shapes.

In *"A History and Interpretation of Aircraft Icing Intensity Definitions and FAA Rules for Operating in Icing Conditions"* [12], Jeck criticizes the current taxonomy used for reporting icing conditions as it raises a number of uncertainties and does not give any readily measurable means for a pilot to recognize the different icing intensities in flight. The author goes on to argue that the icing intensities are aircraft dependent and shows how the regulatory system has adapted to interpret the current icing definitions. Finally, this article proposes several methods of redefining the intensity scale based on measurable quantities such as liquid water content, rate of ice accretion or the effects on the aircraft.

A new method of defining aircraft specific icing severity is then proposed based on the accretion time required to achieve a certain depth [13]. A typical icing scenario is defined and using computer software, the rate of ice accretion and final thickness are predicted for the allotted time frame.

In *"Characterizations of Aircraft Icing Environments that Include Supercooled Large Drops,"* [14] the authors study the icing environments recorded in test flights to determine the relationships that exist between liquid water content (LWC), median volume diameter (MVD) and temperature. One of the more significant conclusions of this paper is that the Appendix-C curves do not adequately represent all the icing environments found in nature, as 8% of the Canadian Freezing Drizzle Experiment flights had MVD greater than 40 microns.

Current methods and factors for determining the criticality of ice shapes, namely the handling and performance characteristics are presented in the research by Bernstein, Ratvasky, Miller, and McDonough [15]. A thorough review of the current literature in the area of experimental measurements and analytical predictions of the aerodynamic effect of in-flight icing is provided, along with a synthesis of the performance data. The report makes an interesting observation: that it may be "practical to make design and certification decisions weighting airfoil sensitivity more heavily than shapes determined using available tools" [15]. This suggests that rather than only focus on the critical ice shapes, designers, certification agencies and operators should pay greater attention to the aerodynamic consequences of ice accumulations.

Petty and Floyd [4] examine the quality of data that is available to analyze the in-flight icing problem in the United States. Occurrences are then distributed according to their segment of aviation operations, either General Aviation, Part 135 operations or part 121 operations. Results show how the number of occurrences varies by month of the year, phase of flight, level of pilot training and geographical location.

Several authors have made attempts at developing novel ways of predicting in-flight intensities such as Jeck [13] and Politovich [16]. However in both cases, the fundamental criterion for determining intensity is the rate of accretion on the airfoil. This does not address the issue of performance degradation of the aircraft. Jeck does speak to a new method that involves qualifying icing intensity based on the effect it has on aircraft that are flying in the region, but does not offer a predictive measure of performance degradation.

2.3. Regulatory Literature

In 1997, the FAA assembled a team of experts to develop an In-flight Aircraft Icing Plan [17]. In this plan, the authors provide a list of tasks that are aimed at improving the safety of air travel with regard to in-flight icing. The team's tasks are to improve training, improve the dissemination of weather information, improve regulations and guidance related to certification, consider a comprehensive redefinition of certification envelopes to include SLD, and develop guidance material on ice accretion shapes and roughness as well as the effects on performance, stability and control. Since this plan was published, many hours have been devoted to studying the effects of icing and many papers with the results of this research have been published, however the regulatory changes have been remarkably slow in materializing, and often only arise in the form of recommendations rather than enforceable regulations or airworthiness directives.

In 2004, a safety recommendation memo regarding the performance of the Cessna 208B was sent to the Honorable Marion C. Blakey at the FAA from the National Transportation Safety Board (NTSB) [18]. In this memo the NTSB highlights the many operational issues that the aircraft experiences when it encounters in-flight icing conditions, as well as the lack of adequate guidance material provided to pilots. The memo points out that pilots are "not consistently provided with pertinent cold weather operation information." [18] The NTSB goes on to make several suggestions for the FAA to remedy these problems.

In 2004 Ells and Hummel[19] perform a thorough review of the legal requirement for aircraft operations in icing condition is provided. The differences between anti-icing and deicing methods are described, as well as the common methods that are used to remove ice from the aircraft. A description of the certification process is made, including the requirement to perform analysis of the ice accumulation in a 45-minute hold, and the need to show that the degraded flight characteristics, while expected, are not worse than the aircraft certification standards. In addition, this advisory includes a description of the procedures for existing icing conditions, and highlights the importance of being aware of the in-flight icing limitations of the aircraft being operated.

In 2005, the FAA released an Airworthiness Directive [20] that requires the revision of the flight manual of the Cessna 208B to include the following statement: "WARNING: The stall warning system has not been tested in all icing conditions and should not be relied upon in icing conditions." Instead of having the manufacturer or operator remedy the dysfunctional system, the FAA has blatantly left the pilot high and dry when operating in icing conditions.

Then, in 2006, the FAA released a Safety Alert for Operators, regarding in-flight icing for turbo-propeller powered airplanes [21]. The purpose of this alert was to increase awareness and emphasize the importance of the limitations and procedures in place for in-flight icing. Pilots are reminded to activate de-icing boots at the first sign of ice accretion and that it is imperative to maintain airspeed, as "in many icing events airspeed decreased from cruise to stall in less than three minutes."[21]

2.4. Literature Review Conclusion

While much has been done to characterize the effects of icing and improve awareness, there remains much to be done in terms of implementing safety management systems and strategies to mitigate risks. Such systems would continue to improve awareness, while providing important information to the pilot about the performance and handling characteristics of the aircraft. Moreover, this would give the regulatory team another tool to improve certification standards and better manage regulatory changes within a safety management framework.

3. In-Flight Icing Hazard

How does the in-flight icing phenomenon occur and why is it a problem?

An aircraft operating in high humidity or overcast conditions and at below freezing temperatures risks encountering supercooled liquid water droplets in various phases of flight, particularly at takeoff, on approach and holding or during landing. The supercooled precipitation occurs when droplets fall from a region of warm air, above freezing into a region of cool air (below freezing). This phenomenon occurs most often at the intersection of warm and cold fronts, as shown in figure 1 below.

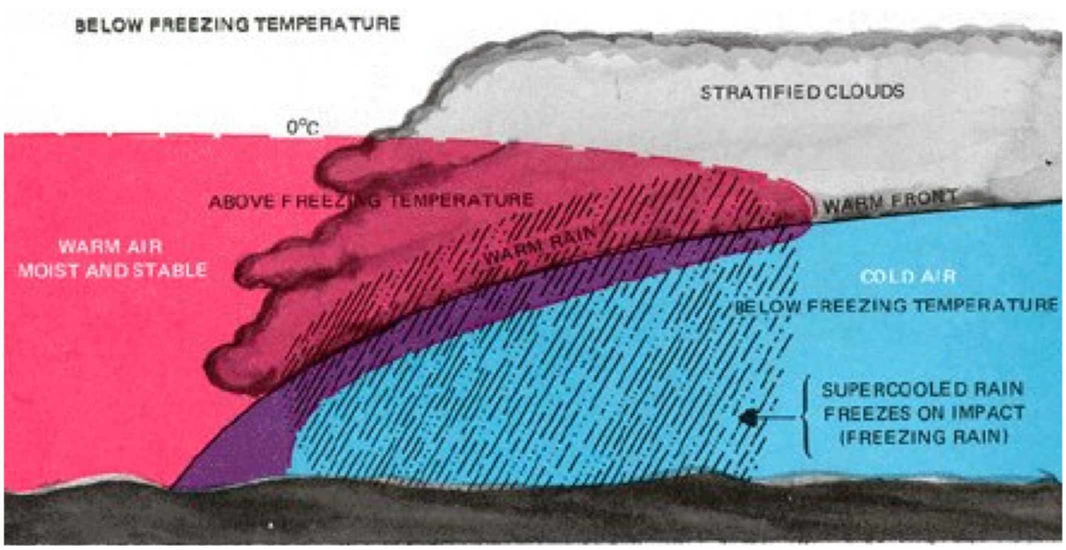

Figure 1 – Formation of supercooled liquid droplets [22]

These droplets, still in the liquid phase despite their temperature being below freezing, hit the aircraft and their heat of fusion is released causing them to freeze on impact or to run down in the chordwise direction and freeze further aft of the point of impact.

Figure 2 – Ice accumulation on the wing's leading edge

Such accumulations, as shown in Figure 2, immediately introduce roughness on the surfaces and gradually change the aerodynamic profile of the wing. The smooth flow of air over the wings is disrupted and the aircraft's aerodynamic properties as well as its stability and control are adversely impacted.

Leading edge flow separation and early transition to turbulence can suppress the leading edge suction and increase drag. In general, subsonic airfoils avoid leading edge flow separation by incorporating into the design a rounded leading edge and a camber to reduce adverse pressure gradients on the upper surface [23]. Despite these design considerations, the presence of roughness on a wing causes the flow to turn turbulent sooner, thus more energy is lost from the air, drag is increased and lift is decreased. The resulting degraded performance increases the aircraft's stall speed and decreases its angle of stall, making flying particularly dangerous during low speed maneuvers like takeoff, landing and holding.

In situations where the aircraft's performance is degraded due to icing, some of the current stall protection systems are not able to alert the pilot that the stall margin has been significantly reduced [20]. The consequences of underestimating or ignoring the effects of surface contamination and reduced stall margin are substantial and can complicate stall recovery.

Ice that accretes on an aircraft has been classified into three categories. Ice that forms at temperatures below -10°C and in clouds with low liquid water content is known as rime ice. Rime ice remains reasonably aerodynamic in shape, though the roughness that forms can still cause important performance degradations. At temperatures ranging from -3°C to 0°C and in clouds containing higher levels of liquid water content, the ice that forms is known as glaze ice; these icing conditions cause the droplets to flow as water on the surface, refreezing further down and producing ice shapes that are very rough and non-aerodynamic, causing substantial performance degradation. The regime between these extremes creates what is known as "mixed ice".

3.1. Current Hazard Mitigation

There are three general philosophies to dealing with the problem of in-flight icing: prevention, reaction and avoidance. Ice formation can be prevented by adding energy in the form of heat as in thermal anti-icing, which stops water droplets from freezing or evaporates the water altogether. This heat can be delivered either as hot air from the engines through piccolo tubes that run along the leading edge of the wing, or through the incorporation of electrothermal mats into the wing's surface. Alternatively, one could prevent ice accretion by chemically depressing the freezing point by dispersing a solution over the protected surfaces, similar to the glycol deicing that is performed prior to takeoff in cold weather.

In aircrafts that utilize reactive measures to tackle ice accretion after it as accreted, the ice can be cyclically removed through intermittent thermal or mechanical systems. A popular mechanical method known as the de-icing boot functions by pneumatically inflating a rubber membrane on the leading edge of the wing, which breaks the ice surface bond allowing the particles to be swept away in the airflow. The figure below shows the typical arrangement of boots on the leading edge of a wing. This research focuses on aircraft equipped with de-icing boots, as they are certified for flight into known icing conditions and allow ice to accumulate on the wing and thus must manage performance degradation.

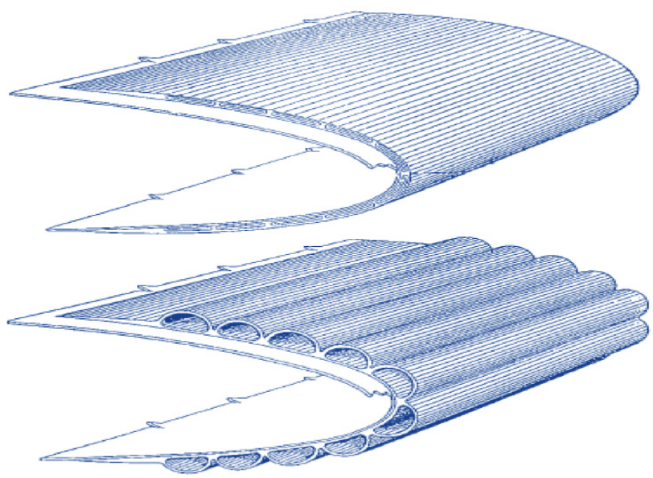

Figure 3 – De-icing boot retracted (top) and expanded (bottom)

3.2. Aircraft Certification and Regulations

Managing this hazard with government regulation

Aircraft certification is a complex and tedious process that establishes requirements that must be met by airlines and aircraft manufacturers to ensure a standard level of operational safety and airworthiness of an aircraft. The final result of a certified aircraft is a declaration "in legal form" from a specified governmental agency that an aircraft and its parts meet all "the applicable requirements" [24]. These requirements are established to ensure that aircrafts are "designed and built according to studied and tested criteria to fly in safe conditions" [24]. Therefore the aircrafts are designed to fly within "allowable limits", meaning they can operate safely within a certain range of conditions based on the "flight envelope" they were designed for. This certification is known as airworthiness, and it is critical for pilots to be notified of these limits either through the flight manual or training or placards in the cockpit [24].

When a company or individual files an application to certify an aircraft it can request that the aircraft be certified for flight into icing conditions or not, depending on the configuration of the aircraft. As a result, aircraft fall into one of three categories when it comes to flying in icing conditions. The first category is for aircraft that have no ice protection equipment and which are not certified for icing conditions. The second is for aircraft that have ice protection equipment in the event of an emergency, but are not certified for such flights. These ice protection systems (IPS) are commonly known as "non-hazard" systems and are meant to provide the pilot with some protection in "inadvertent icing encounters"[19]. Finally, the aircrafts that are considered in this study are equipped with ice protection systems and are certified for flight into known icing.

Aircraft that do obtain certification for flight into known icing conditions must be capable of operating safely in the continuous maximum and intermittent maximum conditions defined in Appendix C of the FAA's Title14 CFR Part 25. The problem with this envelope is that "it was created before the latest research into supercooled large droplet conditions, such as freezing rain or freezing drizzle.” [25] As a result, such conditions are not included in the envelope, despite being a regularly encountered atmospheric situation.

In order to achieve compliance with the airworthiness safety requirements, it must be shown that the aircraft’s performance, controllability, maneuverability, and stability are not less than aircraft’s uncontaminated airworthiness requirements [26]. Therefore, to obtain certification with ice protection provisions, the applicant must show the adequacy of the ice protection system pursuant to the aircraft’s operational needs. In order to verify that the ice protection system is effective, “the airplane or its components must be flight tested in various operational configurations, in measured natural atmospheric icing conditions” [26]. In addition, laboratory dry air or simulated icing tests may be used as part of the ice protection analysis along with flight tests in simulated icing conditions or flight dry air tests that evaluate the ice protection system as a whole [26].

Four intensity levels characterize in-flight icing conditions: trace, light, moderate and severe. The exact definition of the icing reporting table can be found in Appendix A. These levels are meant to convey a level of risk associated with the atmospheric conditions. However, icing conditions impact each airplane differently, a fact that is not reflected in the definitions of icing severity nor is it adequately considered in the aircraft’s operational limitations for flight in icing conditions.

The regulations and certification requirements are contained in the Federal Aviation Administration's Code of Federal Regulations, hereinafter referred to as CFR. Title 14 of the CFR deals with aeronautics and space, and is divided into parts according to the regulation types. There are two main areas that must be considered when dealing with in-flight icing. The first is the aircraft's design and its suitability for flight, which was described above as airworthiness. The second area ensures the aircraft is flown within its design limits by imposing operational regulations based on aircraft size and airworthiness category.

3.2.1. Airworthiness Certification

There are several parts of the Code of Federal Regulations Section 14 Aeronautics and Space that are pertinent to managing the risk of in-flight icing. Part 23 contains airworthiness standards for airplanes in the normal, utility, acrobatic and commuter categories. These aircraft are characterized by their takeoff weight, which is not to exceed 12,500 lb, except for commuter planes, which cannot exceed 19,000 lb In § 23.207 Stall Warning paragraph e) the regulations state that "[…] the stall warning must begin sufficiently in advance of the stall for the stall to be averted by pilot action taken after the stall warning first occurs." Thus regulations require that such aircraft be equipped with stall warning systems, and that the stall warning must alert the pilot in advance of a stall so that he or she may recover. However what is not addressed is how the stall warning system should adjust to account for the reduced stall margin caused by in-flight icing. Certification for ice protection under § 23.1419 states only that "tests of the ice protection system must be conducted to demonstrate that the airplane is capable of operating safely in continuous maximum and intermittent maximum conditions, as described in appendix C of part 25." Where the terms "Capable of operating safely" refer to the performance stability and control characteristics that must remain within the tolerances set in Part 23 subpart B.

Part 25 describes the airworthiness standards for transport category aircraft, which are defined as planes equipped with turbine engines, having more than 10 seats and a maximum takeoff weight of more than 12,500 lb. Turbo propeller aircraft with greater than 19 seats and a takeoff weight superior to 19,000 lb also fall in this category. The requirements for certification of the ice protection system are similar to that of Part 23 aircraft, except that Part 25 aircraft require an ice detection system that will either automatically activate the ice protection system or alert the crew to activate it. In addition, the ice protection system must be designed to operate continuously once activated.

3.2.2. Operations Regulations

While the previous regulations deal with the design, manufacture and testing of the aircraft, there are operational regulations that must be followed to ensure that the safety measures that were integrated into the design of the aircraft function as intended. Regulations in Part 91 refer to the general operating rules for all aircraft, Part 121 pertains to specific operating requirements for commercial aviation and Part 135 addresses issues specific to commuter aircraft operations. Part 125 deals with the special airworthiness certification requirements of aircraft with a payload capacity of more than 6,000 lb or greater than 20 seats, as well as the operational requirements and rules governing persons on board the aircraft.

Under § 91.527 paragraph b), no pilot "may fly under IFR [Instrument Flight Rules] into known or forecast light or moderate icing, or under VFR [Visual Flight Rules] into known light or moderate icing," unless the aircraft is certified for such flight. Moreover, paragraph c) of the same section states that "no pilot may fly an airplane into known or forecast sever icing conditions" except if the airplane has a certified ice protection system. Examining the definition of severe icing from the airframe icing reporting table, included in appendix A of this report, one cannot help but be puzzled as it states that "The rate of accumulation is such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary." Therefore it is permissible for an aircraft to enter severe icing; as long as it is certified for flight into icing conditions, even if the very definition of severe icing is that the ice protection equipment is not capable of maintaining safe flight. Such inconsistencies create confusion, and should be corrected through the implementation of an aircraft specific safety risk management framework. Similar logical flaws can be found in § 121.629, § 125.221 and § 135.227.

These severity definitions do not elucidate what the risk are for the different aircraft, they do not consider what flight phase the ice is encountered in, nor do they address the types of ice that accrete. They require prolonged exposure simply to determine which level of severity is being encountered, and can mislead pilots into thinking that a "light" icing encounter is not a threat to the safe operation of the aircraft or that a certified aircraft can safely operate in severe icing conditions. No measurable quantities are defined for each severity level, except for a "rate of accumulation”, which pilots have little means of measuring with any accuracy. A more aircraft specific means of describing the risk, which could be determined based on current information provided prior to takeoff would enable pilots to be better prepared to handle risks, and manage any performance degradations.

4. Accident Database Analysis

Identifying in-flight icing “hotspots”

Having described the in-flight icing phenomenon and current strategies for mitigating this hazard, the report will now examine the results of these strategies by means of an analysis of global in-flight icing accidents and incidents. The information is collected from the International Civil Aviation Organization (ICAO) accident and incident data reporting database (ADREP)[27]. The database is managed using ECCAIRS software, which characterizes events according to several fields such as: Occurrence Category, Occurrence Class, Injury Level, Severity, Date and Location.

There is distinction to be made between the terms accident and incident. Accidents are defined by Wells [1] as events that have a significant consequence such as an injury, a fatality or major damage to the aircraft. Whereas an incident is an event other than an accident where degradation in safety occurred and an accident could have ensued. The purpose of this analysis is to evaluate safety degradations, and, as a result, both accidents and incidents are combined into icing events and the terms are used interchangeably.

ICAO encourages the exchange of safety information through mandatory, as well as voluntary reporting mechanisms. Member states are required to report accidents according to Chapter 7 of Annex 13 of the Chicago Convention for aircraft over 2250 kg. Reporting to ICAO is not required for aircraft under 2250 kg. This would explain any discrepancy between the number of events included in this study, when compared to similar studies conducted by Petty and Floyd in 2004 [4], or those conducted by Green in 2006 [3], which include many lighter aircraft involved in general aviation incidents. The voluntary incident reporting system should capture safety lapses that did not result in a major accident, but that still represent a deviation from requirements. Obviously, the voluntary system must be non-punitive to encourage the exchange of information.

4.1. Analysis Methodology

The icing incidents and accidents used for this study were found by querying the ECCAIRS database software system. This database contains events having occurred since 1970. The following parameters were used in the query:

Occurrence Category = Ice / Icing

Icing Intensity = Light / Moderate / Severe

This resulted in a list of over 350 events involving icing from every corner of the globe. A manual revision of the events revealed that ground icing was the primary factor for 27 incidents. Consequently these events were removed from the list, as ground icing is not the focus of this study. The final list contains 323 events that are described by the following details:

1. State reporting
2. Date
3. Aircraft Manufacturer
4. Aircraft Model
5. Aircraft Registration
6. Operation Type
7. Flight phase
8. Latitude
9. Longitude
10. Number of Fatalities
11. Air Temperature (when available)
12. Icing Intensity (when available)
13. Precipitation Type (when available)
14. Amount of Cloud Cover (when available)

Some of the above data fields are critical to the analysis such as: aircraft type, flight phase and meteorological information. Trends in the data are identified to determine which conditions combine simultaneously in a large percentage of occurrences. These combinations represent hazardous icing scenarios that will be evaluated through a detailed examination of the accident report, to determine the aerodynamic consequences and associated level of risk.

4.2. Data Visualization and Results

The visual safety management tool ArcGIS is one of the many tools used by the Integrated Safety Management Section (ISM) at ICAO to analyze the vast amounts of aviation data. In this case, ArcGIS is used to geographically position the accident using the latitude and longitude data provided in the accident report. ArcGIS also contains other relevant information such as global average temperature and precipitation distribution, as well as global air traffic densities, and air traffic routes. The information can then be displayed in layers on the map, allowing the simultaneous visualization of independent data sets. Figure 4 below shows the global distribution of reported accidents and incidents related to in-flight icing.

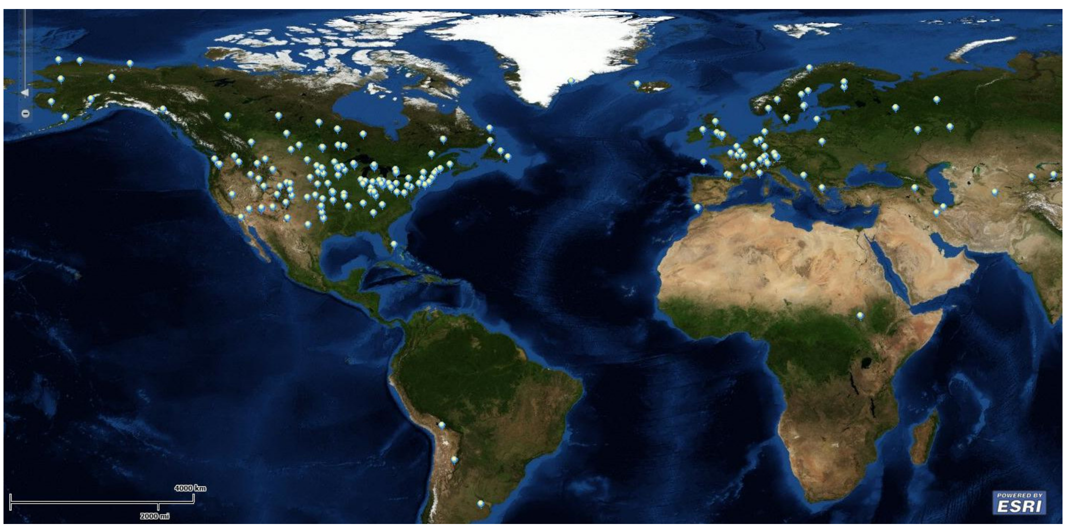

Figure 4 – Global distribution of reported in-flight icing occurrences

This tool makes it possible to quickly visualize where accidents are concentrated and correlate this to the temperature and precipitation levels, as well as traffic concentrations in these regions. In addition to the meteorological conditions, the density of traffic in an area can be a contributing factor for regions with more recorded icing encounters. Most in-flight icing accidents are concentrated in high traffic areas. However, many emerging economies are experiencing rapid growth in air traffic. For example according to traffic data presented by the International Air Transport Association (IATA), the Asian-Pacific air traffic market growth is out-pacing all other regions of the world, and with a combined GDP growth forecast to hit 6% in 2011, over three times the forecast in the United States or Europe, it will continue to experience such increases well into the next decade [28].

The implication of rapid traffic growth is that a hub and spoke network will develop to satiate the increased demand for air travel. Such demand will continue to be fueled by the increasing wealth of individuals in rural areas who will find air travel more convenient and more affordable. A lack of adequate rural road networks in developing countries can make it difficult for travelers to reach airline hub cities by car or bus. The higher profit margins airlines can expect on the long haul international travel that generally operate out of hubs promotes the business practice of feeding these hub cities with smaller, more expensive regional flights, often operated by propeller driven aircraft. With larger aircraft departing from hub cities, more regional aircraft will need to fly in to feed them, and so as international travel increases, the domestic and regional traffic will necessarily increase. This trend impacts the amount of aircraft that will be exposed to icing, but also raises the question of adequate pilot training for handling aircraft with contaminated wings or control surfaces, especially in developing countries in warmer climates. Unfortunately, the issue of pilot training in developing regions is outside the scope of this project, however it remains a critical part of addressing the future of in-flight icing safety.

The following three figures highlight in red regions with high traffic and a large proportion of in-flight icing accidents, while regions highlighted in yellow have similar meteorological conditions to the red regions and are predicted to experience an increase in air traffic volumes as per the aforementioned IATA study – making them vulnerable to future in-flight icing incidents. In figure 5, the impact of traffic density is made evident by overlaying the accident location with number of departures in a city.

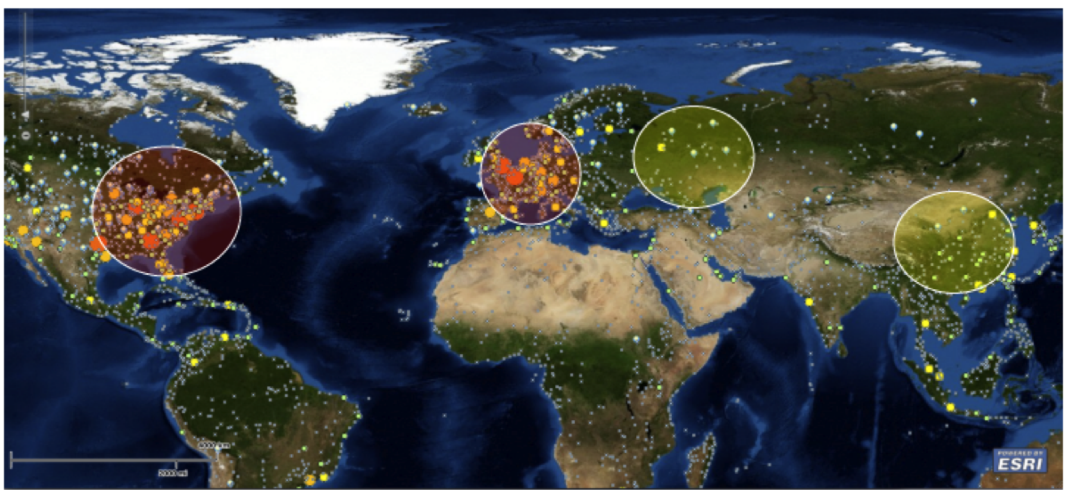

Figure 5 – Global traffic distribution with in-flight icing occurrences

Figure 6 below shows the distribution of icing accidents and incidents versus the average annual ground temperature. It is clear that the preponderance of accidents occur in regions with an annual average temperature between 0°C and 15 °C.

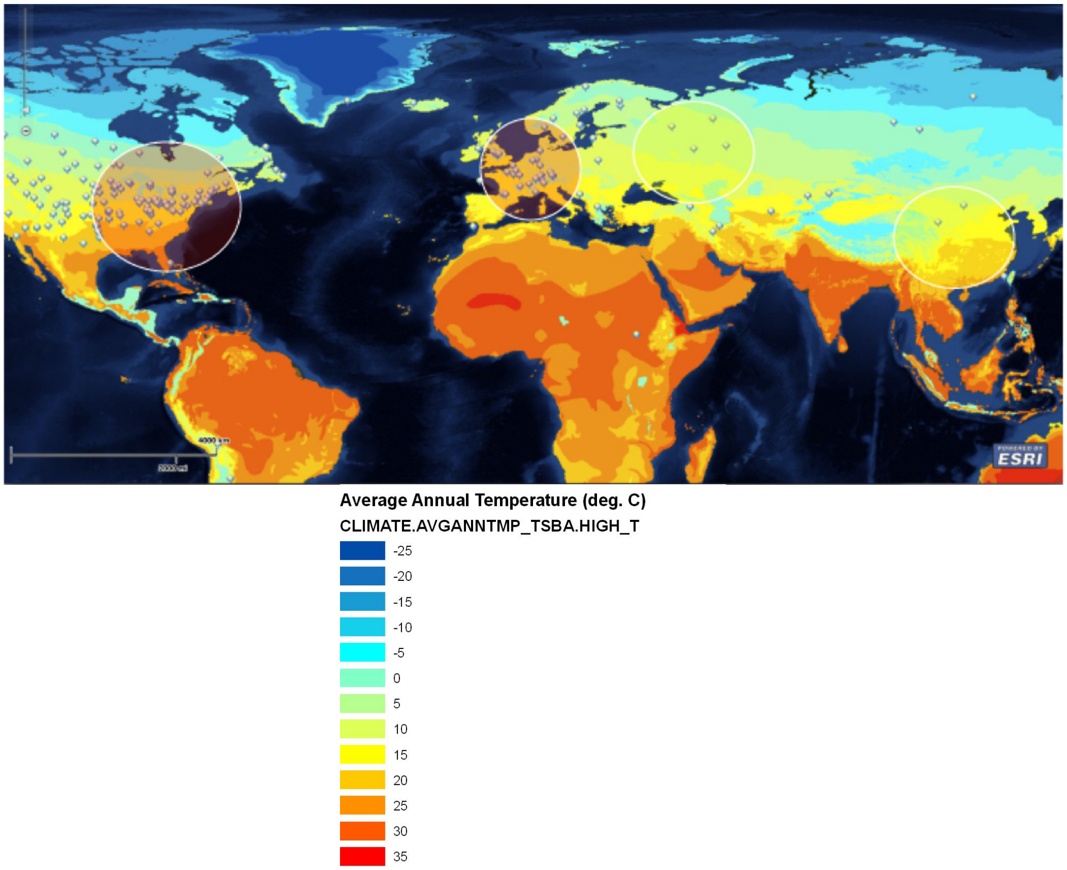

Figure 6 – Global average temperature distribution with in-flight icing occurrences.

Naturally, one is inclined to believe that icing events only happen in cold climates; however the fact is that while it may be relatively warm on the ground, temperatures can be substantially lower at altitude. The rate at which temperature drops as altitude increases, known as the lapse rate, is approximately 6.5°C/km [29]. Therefore, even if the conditions are warm on the ground, a pilot must be aware that there is still a potential for ice to accrete on the airframe, as the temperature and humidity at the planned altitude might be conducive for ice formation. Figure 7 below shows the percentage of accidents as a function of ground temperature. It is obvious that most accidents occur when the ground temperature registers between -5°C and 5°C. At 3000 feet these temperatures shift to approximately between -10°C and 0°C, the hazardous range for glaze ice.

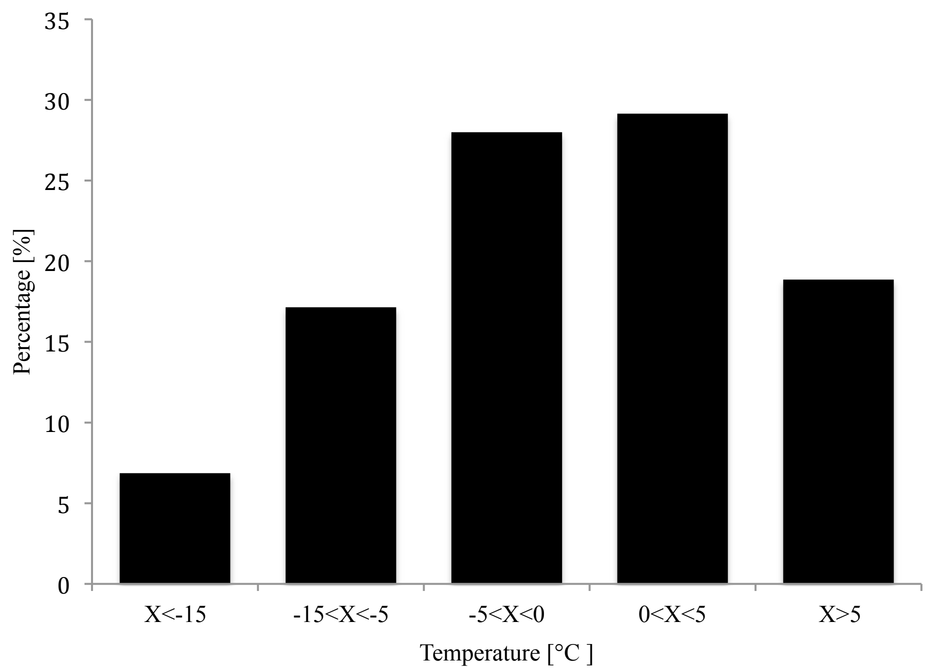

Figure 7 – Percentage of occurrences by ground temperature range [°C]

Figure 8 below shows the distribution of reported icing accidents and incidents versus the average annual precipitation. It indicates that the majority of accidents occur in regions that are subjected to amounts of precipitation in excess of 600 mm per annum.

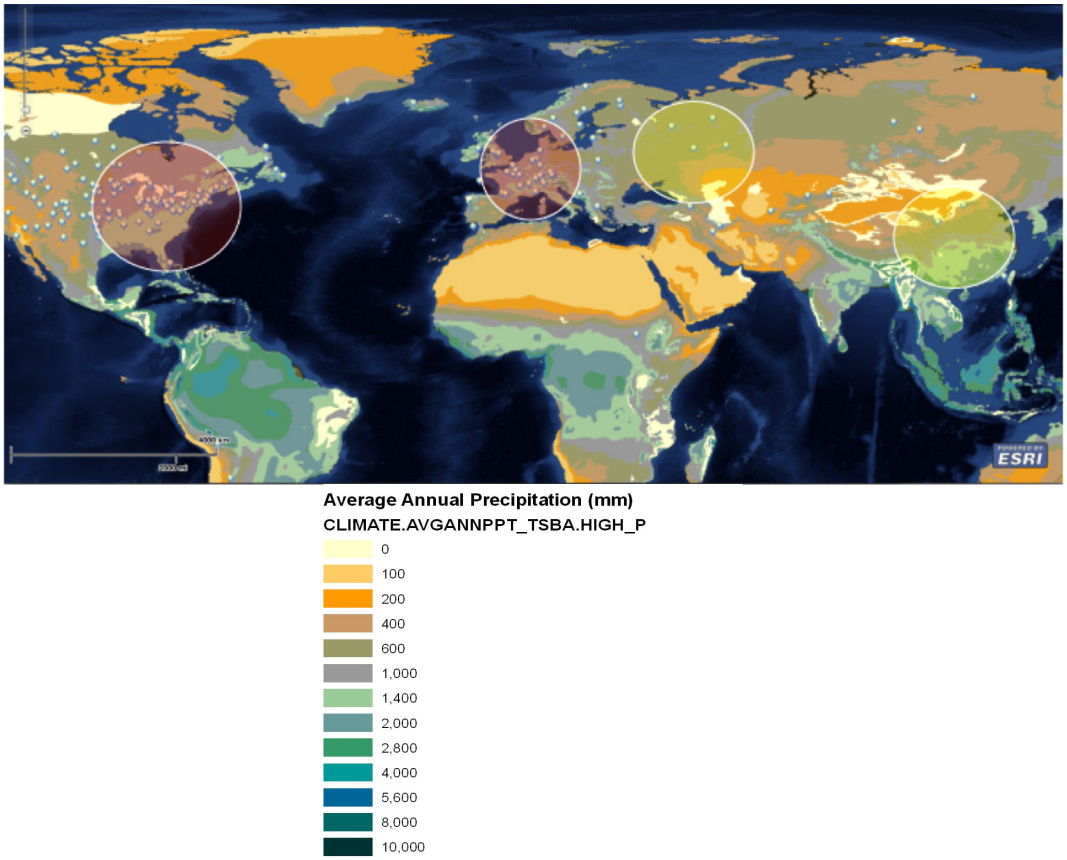

Figure 8 – Global average precipitation distribution with in-flight icing occurrences.

The accidents are also analyzed based on the flight phase at the time of the icing encounter, to determine when the aircraft is most vulnerable to the aerodynamic penalties from ice. It is important to note that the phase of flight in which the incident occurs and the phase of flight during which the ice is accreted need not, and often do not coincide [30]. One of the most common flight phases for icing incidents is the approach phase. These occurrences are highlighted in yellow in figure 9.

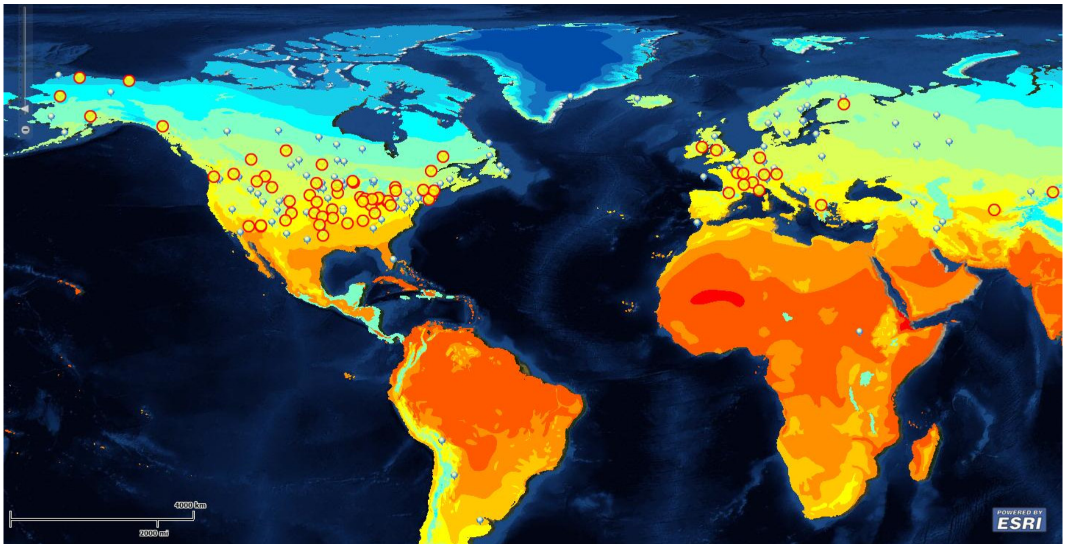

Figure 9 –Distribution of in-flight icing occurrences during approach phase

The reason the approach phase is vulnerable to icing is because the wing surface contamination decreases the stall margin, increasing the speed at which the aircraft will begin to stall and decreasing the stall angle. The reduction in speed that occurs during approach as well as the extension of flaps and the changes in pitch can lead to unexpected behavior as the aircraft operates on the edge of the reduced stall margin. In addition to the aerodynamic considerations, human factors also play a role as the approach stage is a busy one in the cockpit, with pilots focused on communicating with air traffic controllers and preparing for landing. Add to this monitoring the accumulation of ice on the wings, without any reliable tool to do so and with generic rules for determining the severity of the degradation caused by the contamination, and it becomes increasingly evident that a better safety management strategy is required.

The relevance of approach stage accidents is further emphasized in figure 10 below. It is worth noting that a substantial number of accidents reported encountering icing in a low altitude cruise phase. Moreover, these cases stated in the accident report that ice was accreted in cruise however it wasn't until a maneuver was performed, which changed the angle of attack or speed of the aircraft, that the performance degradation was felt.

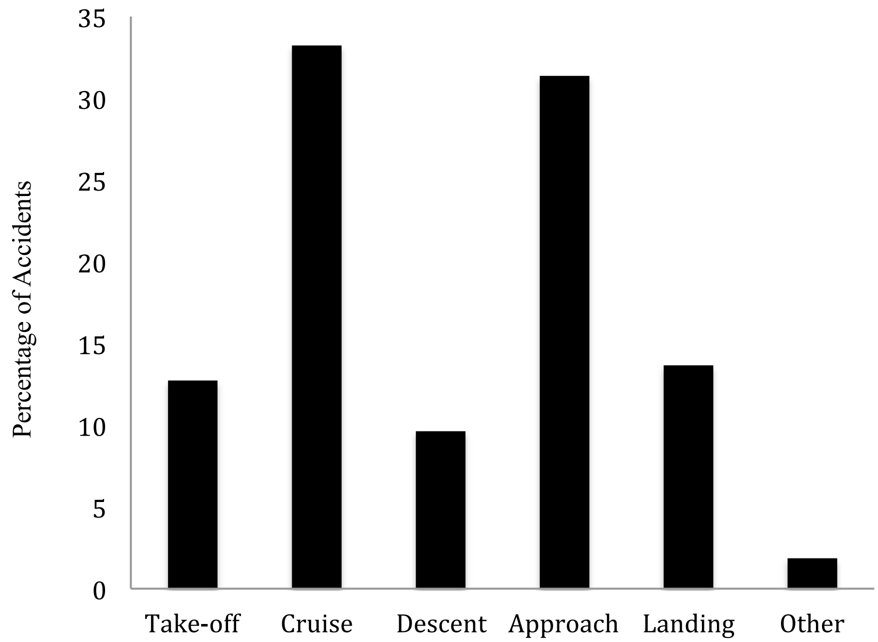

Figure 10 – Percentage of occurrences by phase of flight

The occurrences were also distributed in terms of time of year. Figure 11 clearly shows how the percentage of accidents and incidents varies monthly. This distribution is quite intuitive, as most accidents occur during the winter months of high traffic regions.

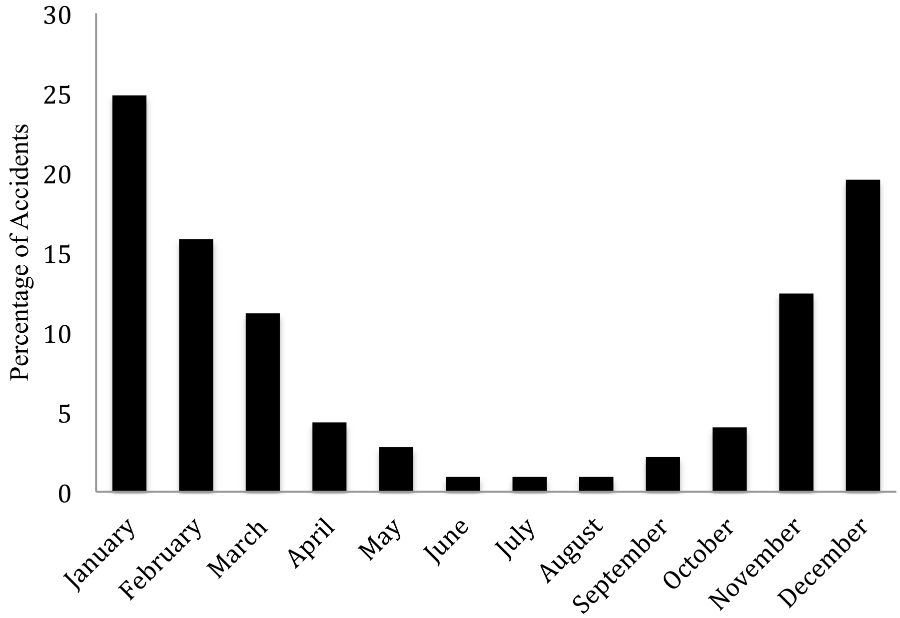

Figure 11 – Monthly distribution of in-flight icing occurrences

In a vast majority of cases where the atmospheric conditions were indicated in the accident report, there was some form of precipitation present at the time of the accident. This indicates that high humidity levels were present at the time of the incident. The different types of precipitation and their rate of occurrence in accident reports are shown in figure 12 below.

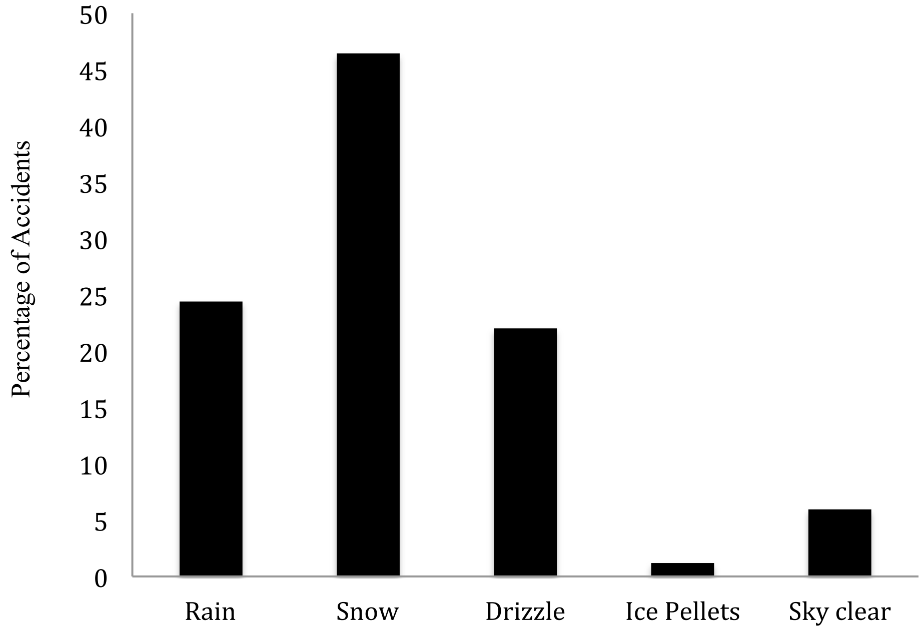

Figure 12 – Percentage of occurrences by precipitation type

The preponderance of occurrences involves smaller propeller drive aircraft. Since these aircraft fly at lower altitudes and at slower speeds than larger transport category aircraft there is a greater probability of them encountering icing conditions [31]. Smaller chord lengths and a smaller leading edge radius can make an airfoil more susceptible to ice accretion. Moreover, the greater ratio of ice thickness to chord length, commonly found on the smaller aircraft is more adverse for icing [32]. In addition, the airfoil type used in the design of a significant portion of the current turboprop fleet, the NACA 23XXX family is found on over 50% of aircraft involved in icing accidents and incidents. Figure 13 shows the distribution of events by airfoil, with the most notable airfoil of the family being the NACA 23012 found on aircraft in nearly 25% of the total events in the database. The work of Abbott and Von Doenhoff [33] has shown that "NACA 230XX sections stall from the leading edge with large losses of lift. A more desirable gradual stall is obtained when the location of maximum camber is farther back, as with the NACA 24, 44- and 6-series sections with normal types of camber"; and they also add: "NACA's standard practice had been to apply 0.011-inch carborundum grains to 8% chord on both upper and lower surfaces. While this standard roughness is considerably more severe than that caused by usual manufacturing irregularities or deterioration in service, it is considerably less severe than that likely to be encountered in service as a result of accumulation of ice, mud..." They go on to demonstrate that the lift of the 230XX series is "greatly" affected by roughness. This is further confirmed by the study on the effect of residual and intercycle ice accretion on airfoil performance [8], which found that the roughness caused by the sand paper does not accurately replicate the performance penalties of even minor ice accumulations. Yet, this is the airfoil section that many experienced aerodynamicists have chosen for a large class of turboprops flying today.

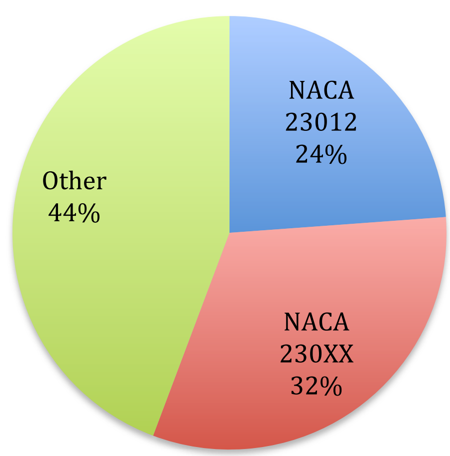

Figure 13 - Percentage of accidents by airfoil type

4.3. Accident Analysis Conclusions

In conclusion, it was found that propeller driven aircraft on approach phase, operating in temperature between -5°C and 5°C are most vulnerable to experiencing in-flight icing problems.

The results indicate that passenger air traffic accounts for 151 of occurrences, while cargo traffic and business traffic are the next closest with approximately 70 occurrences. Over half the icing accidents reported to ICAO are fatal, and amount to greater 1000 fatalities in the last 30 years.

NACA 230XX series and in particular NACA 23012 is a major cause for concern when it comes to in-flight icing as a substantial percentage of the incidents were found to involve aircraft that use this airfoil in the design of their wing. A critic could argue that this airfoil's use in the design of a large number of aircraft involved in accidents is due to the comparatively larger number of such aircraft in service. While this could help justify the disproportionate number of accidents and incidents it should not detract from the responsibility of ensuring the operational safety of aircraft flying in icing conditions. As this study will endeavor to show, it is possible to better understand and manage the risks of in-flight icing by utilizing CFD to predict the performance degradation and using a risk management structure to categorize the level of safety for a particular aircraft in specific icing conditions. With such a system in place, engineers could adjust the design of their aircraft to improve the safety assessment and consequently the aircraft's performance in target areas of the flight envelope.

5. Computational Fluid Dynamics Simulation

Using technology to gain more information about specific consequences of icing exposure.

As the analysis in the previous section concluded, turboprops are more vulnerable to in-flight icing accidents, and while they are more efficient than turbine engines, they are limited to low speed and low altitude operations since their efficiency decreases as speed and altitude increase [34]. Thus turboprop designs favor wings with high lift to drag ratios. Consequently, turboprops are often designed with the NACA 230XX family of airfoils which achieve excellent lift to drag ratios [33]. While they may provide excellent theoretical performance, the NACA 230XX airfoils have proven to be very sensitive to ice contamination. Consequently, the aerodynamic analysis included in this research focuses on the performance of the contaminated NACA 23012 airfoil, but the methodology remains applicable for the study of other airfoils, wing sections or entire aircraft.

5.1. Simulation Methodology

The first step in performing the numerical simulation involves creating the airfoil geometry as well as carefully generating a mesh that will adequately capture the boundary layer and ice accretion phenomenon required for the study. It is widely accepted that the quality and credibility of a numerical simulation is highly dependent on the mesh used to discretize the problem [35]. The details of the creation of the numerical wind tunnel are developed further in Appendix B.

The ice accretion simulation process utilizes three modules in the FENSAP-ICE package. The first module in icing simulation consists of the solution of the compressible Navier-Stokes equations using FENSAP: Finite Element Navier-

Stokes Analysis Package. This provides the necessary information regarding the flow characteristics such as velocity and pressure around the airfoil to the second module known as DROP3D, which computes the collection efficiency distribution by a Eulerian method. Using the impingement limits computed by DROP3D as well as the flow characteristics, heat fluxes and surface shear stresses from the FENSAP module, the ICE3D module predicts the ice accretion shape on the surface.

The objective of simulating ice accretion over the airfoil is to determine the shape of ice formed, as well as the magnitude of the performance penalties that are incurred in a specific combination of atmospheric and flight envelopes. However, prior to simulating potentially hazardous conditions, the present section will demonstrate the validity of the numerical model results by comparing the simulated results with those from wind tunnel experiments.

5.2. NACA 23012 Airfoil Lift Curve

An initial validation run compares the lift curve computed using the flow solver FENSAP to the experimental values from Abbott and von Doenhoff in 1959 [36], which were later confirmed in the experiments by Bragg and Broeren in 2002 [8]. The experiment conditions simulated were for a Mach number of 0.27 and a Reynolds number of 6.4×10^{6}. The data collected by Abbott and Doenhoff over a half century ago is comparable to the results obtained by Bragg and Broeren, despite the former not being able to measure airfoil surface pressure directly, and instead having computed lift coefficients “by integrating reaction pressures on the floor and ceiling of the tunnel” [8].

To simulate the clean airfoil's lift at different angles of attack, the angle sweep function is used in FENSAP to run the flow solutions. The airfoil is assumed to be free of roughness and the turbulent transition point is set to "Free Transition", allowing FENSAP to determine the most suitable location for transition to occur. The solver is run for at least 3000 iterations and the residual convergence is at least 10^{-7} for each angle, as shown for four angles in figure 14 below. The airfoil used has a chord length of 0.914m and an air velocity of 87.7m/s, thus achieving the desired Reynolds and Mach numbers.

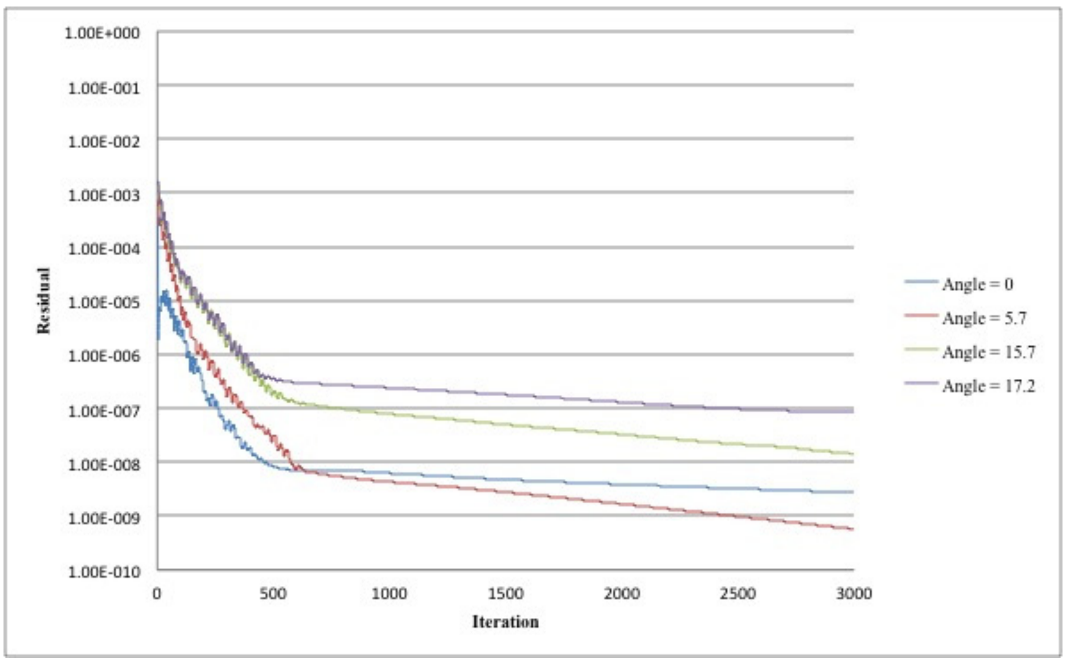

Figure 14 – Clean lift curve simulation convergence for selected angles

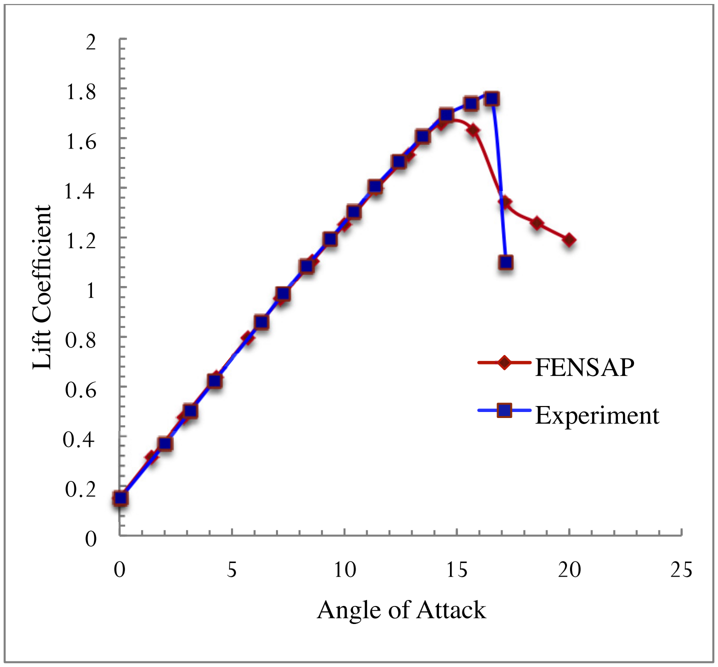

Figure 15 – NACA 23012-clean lift curve

Figure 15 above shows excellent agreement between the simulated FENSAP solution and the wind tunnel experimental results. The maximum lift coefficient differs by less than 4% and the stall angle is 16.5 for the experiment versus 15.7 degrees in the FENSAP simulation. The FENSAP results are used as a reference to which the performance degradations in future simulations will be compared.

5.3. NACA 23012 Pre-activation Ice Experiments

The next step is to validate the drop impingement and ice accretion modules. To accomplish this, several experiments performed from two studies, one on the "*Performance of pneumatic deicing boots*"[9] and the other on the "*Effect of residual and intercycle ice accretions on airfoil performance*"[8] are recreated in the numerical wind tunnel to compare the results.

These experiments were conducted at the Goodrich Corporation Deicing and Specialty Systems Division (DSSD) Icing Wind Tunnel (IWT) located in

Uniontown, Ohio, during March of 2000 by members of a collaborative icing research program. Both studies evaluate the ice accretion on the NACA 23012 for a variety of conditions and exposure times.

In the first study, the researchers investigated the formation of pre-activation ice, which is the ice forming on the clean airfoil surface prior to the activation of the de-icing boot. The tests conducted in the icing wind tunnel are performed at temperatures ranging from -22°F to 32°F (243.15 to 273.15 Kelvin), and with a spray system able to produce water droplets ranging in sizes from 14 to over 40 μm and in density from 0.1 g/m^3 to over 3.0 g/m^3 [9].

The pre-activation test parameters were:

1. The total time prior to activation (Response time)
2. The angle of attack of the airfoil
3. The free stream velocity
4. The static temperature
5. The droplet mean volume diameter (MVD)
6. The liquid water content

Of these variables, only the activation time and liquid water content are varied between simulations to assess the impact of these parameters. Table 1 below summarizes the five experiments performed in the IWT that are to be simulated in the numerical wind tunnel to validate predicted ice shapes for pre-activation ice.

Table 1 – Ice accretion investigation conditions [9]

		Test Conditions		Icing Conditions			
Run	Total Response Time (sec)	Angle of Attack (degrees)	Velocity (mph)	Type	Tst (Fahrenheit)	MVD (mm)	LWC (g/m^3)
A1	41	4	195	MC	14	20	0.45
A2	60	4	195	IM	14	20	1.95
A3	33	4	195	MC	14	20	0.45
A4	324	4	195	MC	14	20	0.45
A5	107	4	195	IM	14	20	1.95

At this stage the comparison between the numerical simulation and the icing wind tunnel experiments is mainly qualitative. Each experimental run concluded with a tracing of the ice shape at a particular cross-section of the airfoil that was deemed to have accreted the most ice. Due to the fact that the particular shape of ice can vary along the span, the primary objective is to show that the quantity of ice accretion predicted by FENSAP-ICE is similar to the amount accreted in the IWT and that there are some similarities in the impingement limits. Each simulation consists of a single iteration of the FENSAP → DROP3D → ICE3D sequence. Each iteration will henceforth be known as a "shot", and therefore a simulation involving multiple iterations is known as "multi-shot", or as is the case for the shapes simulated prior to the activation of the boot using a single iteration: "single-shot".

Results are available for comparison for runs A1, A2, A4 and A5, as run A3 was not traced in the original IWT experiment. However, it would likely resemble the shape obtained in A1.

5.3.1. Run A1 – Maximum Continuous Icing for 41 Seconds

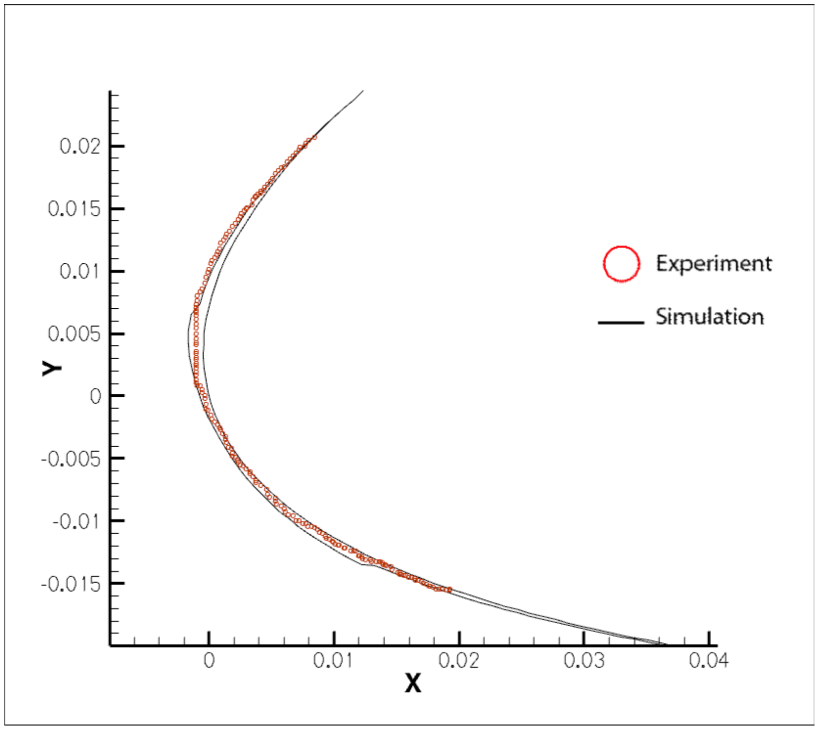

Figure 16 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run A1

Figure 16 shows definite similarities between the shape and thickness of the simulated ice shape and the one traced after the experiment. The impingement limits of the simulation extend further aft than the experiment. However, the thickness of ice accumulation aft of 0.02c is negligible and may not have been captured in tracing and so the impingement limits are considered to be accurately rendered for this run.

5.3.2. Run A2 – Intermittent Maximum Icing for 60 seconds

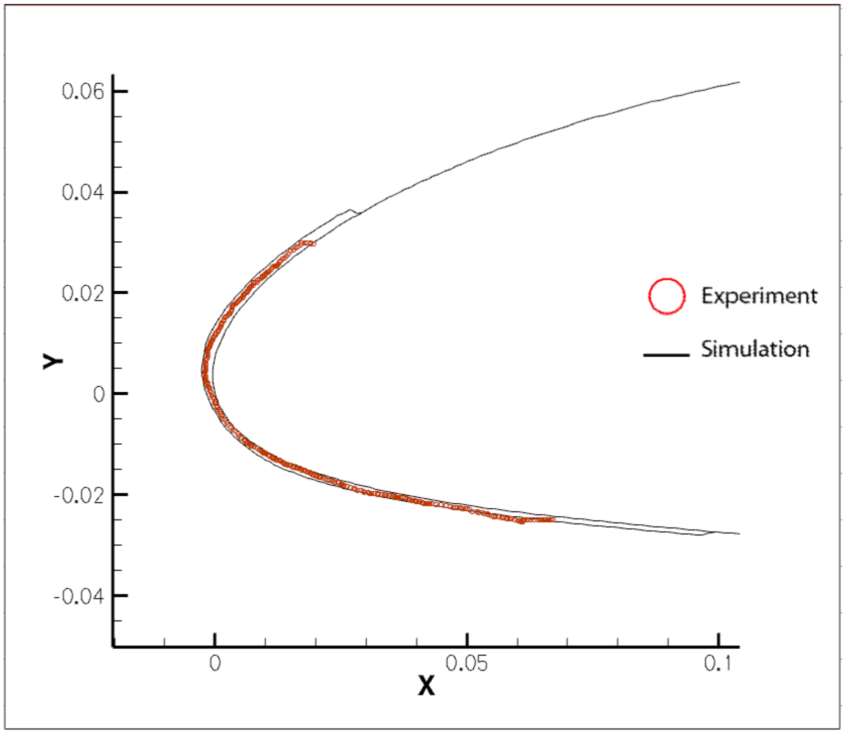

Figure 17 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run A2

Figure 17 again shows excellent agreement between the simulated and experimental results. In this case the simulated accretion extends further aft than the experimental, both on the top and bottom. However, the experimental results indicate that frozen rivulets extended beyond what was traced and thus the impingement limits are considered accurately replicated in the simulation.

5.3.3. Run A4 – Maximum Continuous Icing for 324 seconds

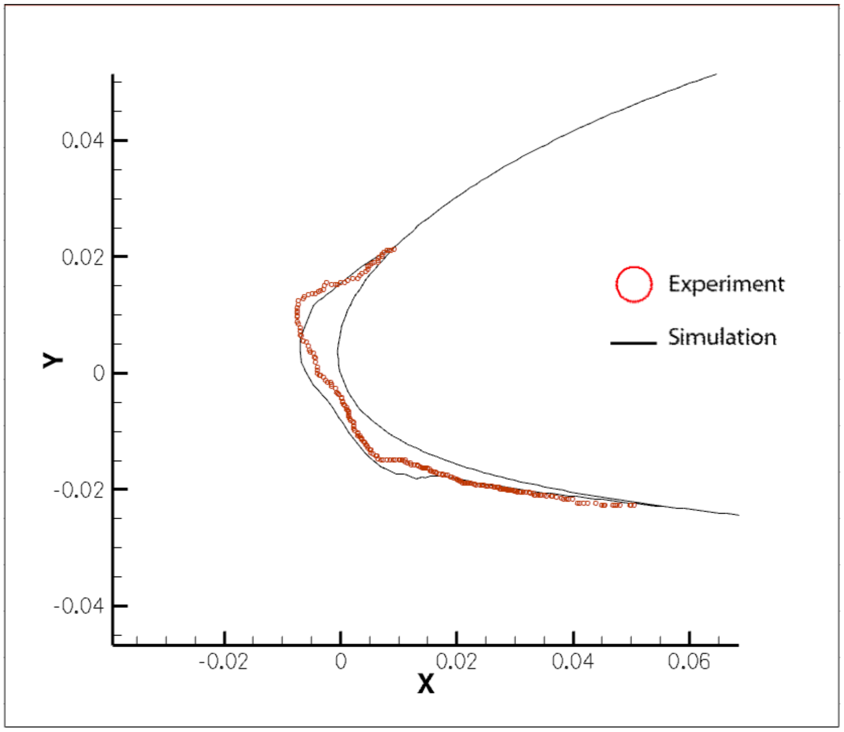

Figure 18 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run A4

Run A4 has the greatest exposure time simulated in these test cases. Figure 18 shows how horns begin to develop on the upper leading edge and how the rough glaze ice produces many irregularities. Such irregularities are difficult to simulate with precision, however the general shape and thickness of the accumulation is captured by FENSAP.

5.3.4. Run A5 – Intermittent Maximum Icing for 107 seconds

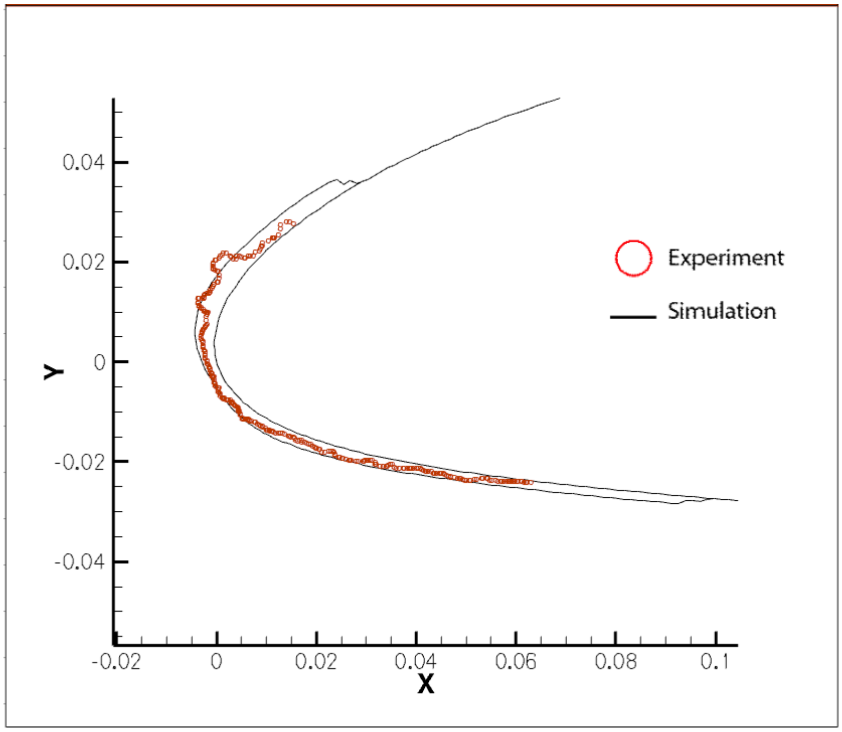

Figure 19 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run A5

As shown in figure 19, The experimental results are characterized by very rough texture, which is not quite captured in FENSAP-ICE's single shot simulation. Again, in this instance the experimental results show the presence of small rivulets aft of the traced accumulation on the lower leading edge, as well as large beads on the upper leading edge, consistent with the impingement limits of the simulated results.

A better roughness pattern can be achieved through the use of multi-shot techniques that iterate between the flow, drop and ice solvers several times throughout the time frame of the simulation, each time adjusting the mesh as necessary after the ice is accreted [35].

5.4. NACA 23012 Inter-cycle Ice Experiments

Next, the experiments performed as part of the study on the effect of residual and inter-cycle ice accretions on airfoil performance are recreated in the numerical wind tunnel. The parameters used in this study are the same as those used in the previous one. However, in this case instead of pre-activation time the variable is the boot cycle time (the time between boot expansions). For each run, the temperature, boot cycle time, LWC, angle of attack and MVD are varied [8]. Table 2 summarizes the conditions for the inter-cycle ice accretion experiments that will be recreated in the numerical wind tunnel.

The activation of the de-icing boots is considered for the approach, as this flight phase represents the highest percentage of occurrences for aircraft equipped with ice protection systems [3, 4]. The boot cycle times are used to determine the amount of ice that would accumulate between cycles (inter-cycle). The FAA report on performance of deicing boots indicates that the cycles can run on 1 minute or 3-minute intervals depending on the severity and duration of the encounter. Generally, 1-minute cycles are used for intermittent maximum conditions, while 3-minute cycles are used for continuous maximum conditions. Such cycle times are said to be representative of the current deicer designs [9].

The inter-cycle ice simulations are characterized as having a surface roughness varying from 0.002 to 0.010 m [37]. Subsequent surface roughness is computed and adjusted by FENSAP-ICE using empirical correlations [6].

Table 2 – Inter-cycle ice accretion conditions [8]

		Test Conditions		Icing Conditions			
Run	Total Response Time (sec)	Angle of Attack (degrees)	Velocity (mph)	Type	Tst (Fahrenheit)	MVD (mm)	LWC (g/m^3)
B1	180	0	175	Mixed	14	20	0.45
B2	180	0	175	Glaze	21	20	0.65
B3	180	4	175	Rime	-4	20	0.25
B4	180	0	175	Glaze	21	40	0.25
B5	60	0	175	Rime	-4	40	0.4
B6	60	4	175	Mixed	14	20	1.95

In this section, as in the previous, the predicted ice shapes are compared to the experimental results from the icing wind tunnel. In addition to the ice shapes, the icing wind tunnel experiments provide a basis to compare FENSAP-ICE lift curve results with the experimental lift curve for runs B1, B2 B4 and B5. The experimental team selected these runs because they had a larger mass of ice, and are said to consist of "worst-case scenarios" [8]. However, as is pointed out in [11], worst-case impingement and worst-case performance do not necessarily coincide.

Multiple sequential iterations of FENSAP, DROP3D and ICE3D are used to better capture the effects of evolving roughness and ice on the fluid flow simulations. For the runs with a response time of 180 seconds, the ice accretion time for each iteration was set to 20 seconds and thus required 6 full iterations. Similarly, the 1-minute response runs were run with an ice accretion time of 10 seconds, again requiring 6 full iterations.

5.4.1. Run B1 – Continuous Maximum: Mixed Ice

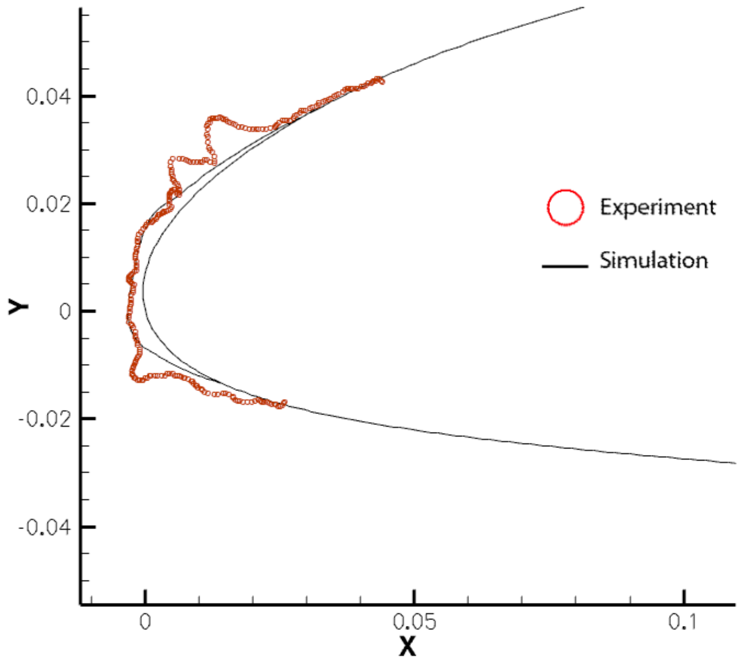

Figure 20 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run B1

The above results show that the FENSAP-ICE software is able to recreate the thickness of the ice at the leading edge. However, even with the multi-shot parameters used, it was not able to capture the horns that protrude at the top of the leading edge. It should be noted that the experimental results are highly dependent on where on the wingspan the ice shape was traced. The experimental team in [8] took all tracings at the mid-span.

The contaminated airfoil is rotated to simulate changes in pitch, and to determine the aerodynamic properties of the contaminated airfoil for different flight conditions. The resulting lift curve is shown in figure 21 below.

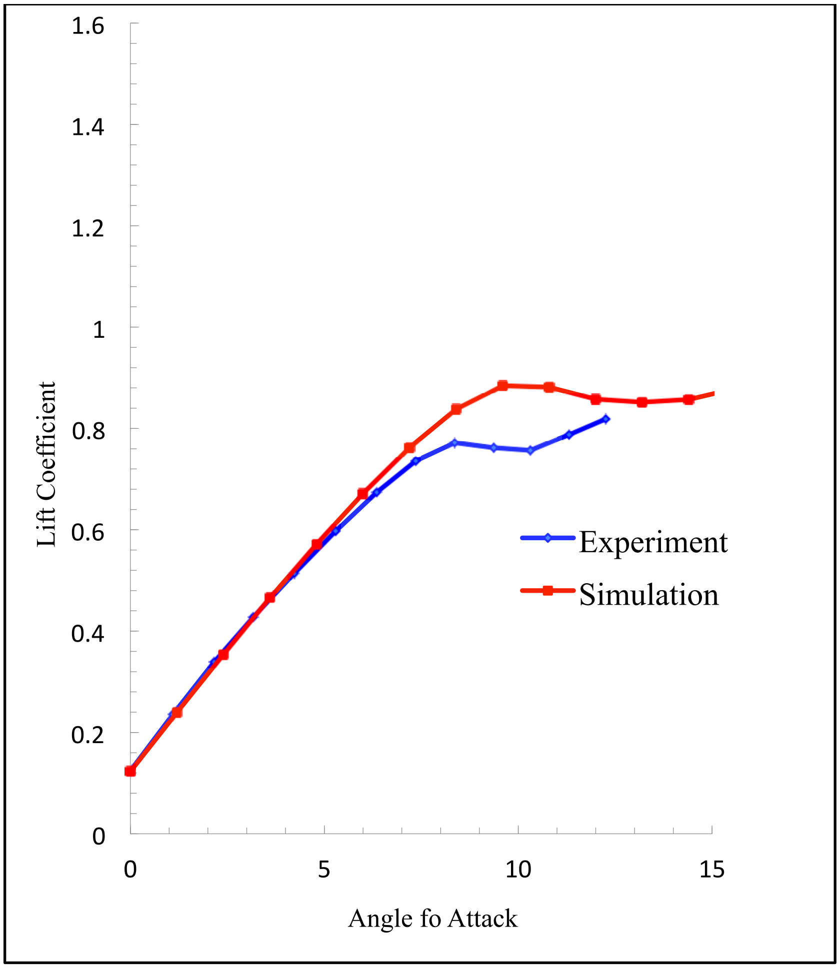

Figure 21 – Comparison of FENSAP predicted lift curve and experimental lift curve – Run B1

Comparing the simulated and experimental results, one can find very good agreement in the linear portion of the curve. Some variation does occur as the pitch of the airfoil approaches stall. The experimental curve exhibits interesting behavior as it stalls early, but regains some lift as it pitches further. Moreover, it shows flow separation 1.3 degrees before this phenomenon is captured in the simulation, and an initial maximum lift of 0.77, 12% less than the simulated value. The large discrepancies can be attributed to the double horn formation on the experimental ice shape. This horn is located on the upper surface of the airfoil, and thus has a larger impact on the lift performance [30].

The simulations were run for 6000 iterations and a convergence of the Navier-Stokes residual was achieved to a level of at least 10^{-7} for each angle. Figure 22 shows the evolution of the residual for four selected angles.

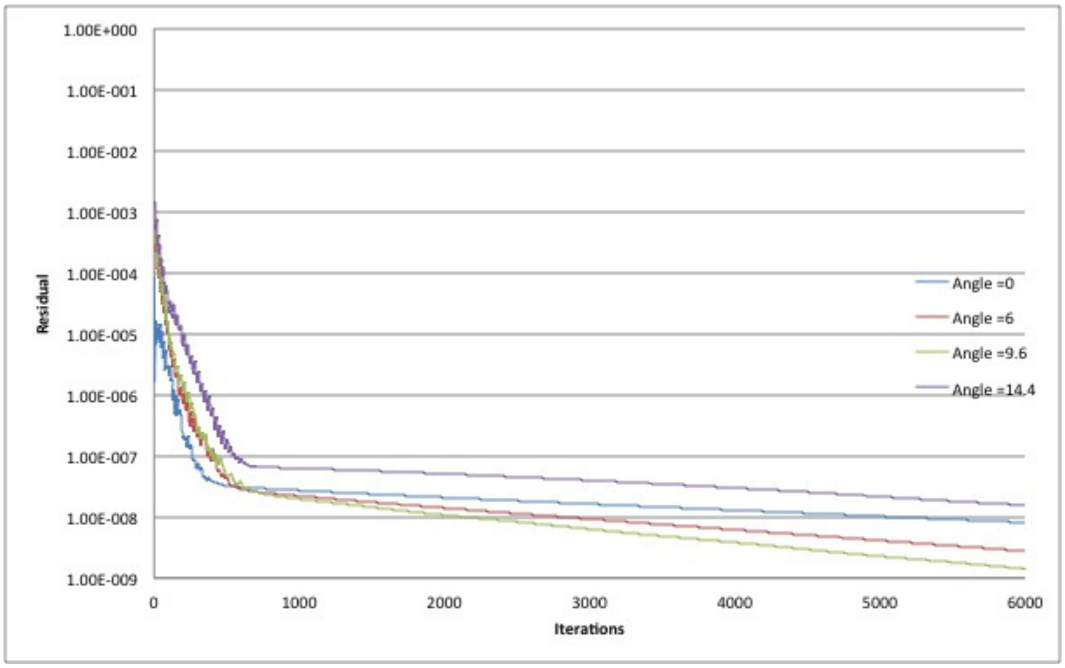

Figure 22 – Run B1 lift curve simulation convergence for selected angles

5.4.2. Run B3 – Continuous Maximum: Glaze Ice

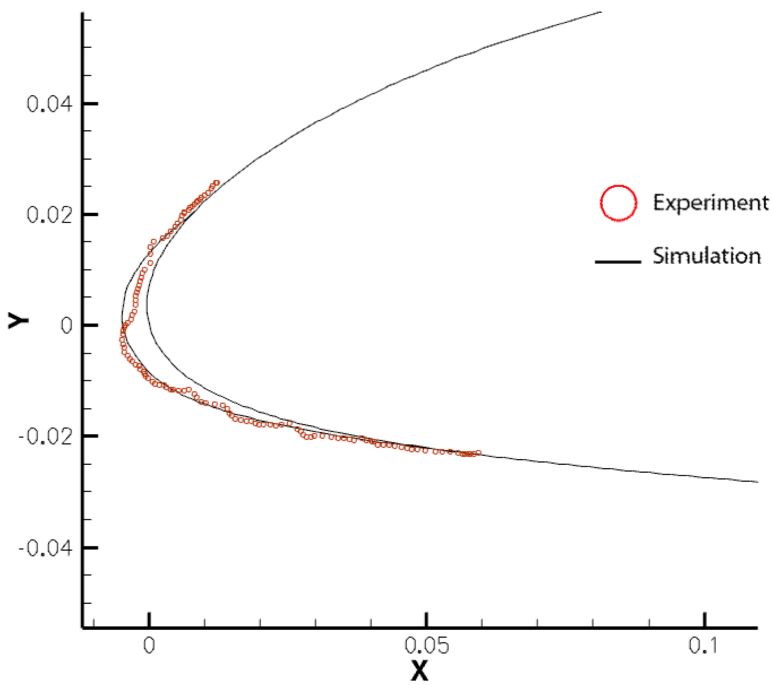

Figure 23 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run B3

The experimental results for this run were not molded, and thus there are no results for the aerodynamic performance with this ice shape. However, comparing the ice shapes in figure 23 shows excellent agreement between the experimental and simulated results.

5.4.3. Run B4 – Continuous Maximum: Glaze Ice

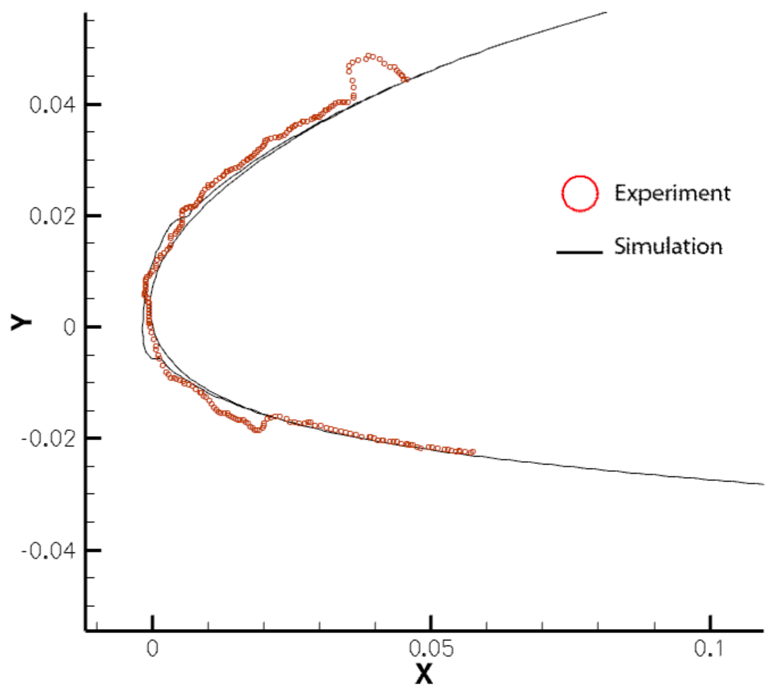

Figure 24 – Comparison of FENSAP Predicted ice shape and IWT Ice Shape – Run B4

In figure 24, the experimental ice shape is very undulated and rough. This is difficult to reproduce with CFD simulations because of the numerical smoothing needed to achieve convergent results. However, the thickness of ice on the leading edge is well represented as well as some undulations. Only the horn on the upper edge was not captured. The aerodynamic performance results from the LTPT are compared to the FENSAP results in the figure below.

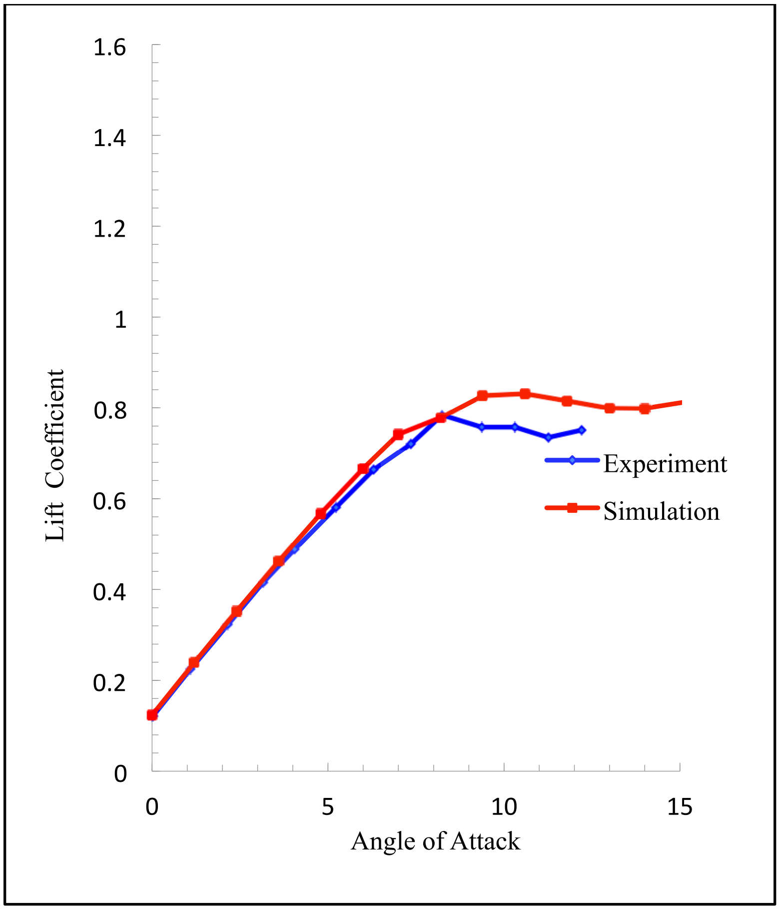

Figure 25 – Comparison of FENSAP predicted lift curve and experiment lift curve – Run B4

The simulated lift curve in figure 25 shows excellent agreement with the experimental results, with less than 5% difference between the value of maximum lift and near perfect match in the slope of the curve. A 1.2 degree discrepancy exists between the stall angle measured by experiment and by numerical simulation.

5.4.4. Run B5 – Intermittent Maximum: Glaze Ice

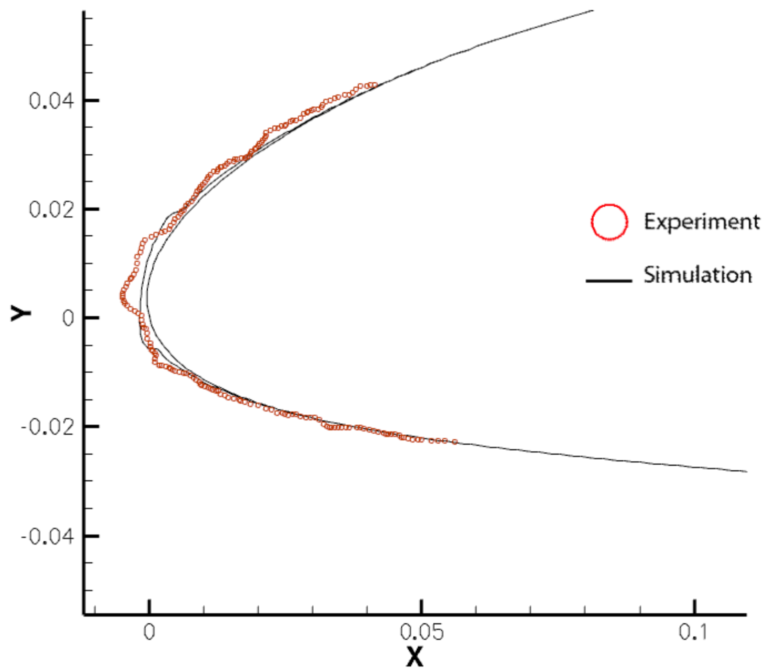

Figure 26 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run B5

It is seen in figure 26 that the thickness of ice at the leading edge is slightly greater in the experimental results than with the FENSAP simulation. However, there is good agreement of the impingement limits on the upper and lower surfaces of the airfoil. As a result of this greater thickness at the leading edge, the experimental contaminated airfoil will exhibit significantly different performance characteristics. The lift curves are compared in figure 27.

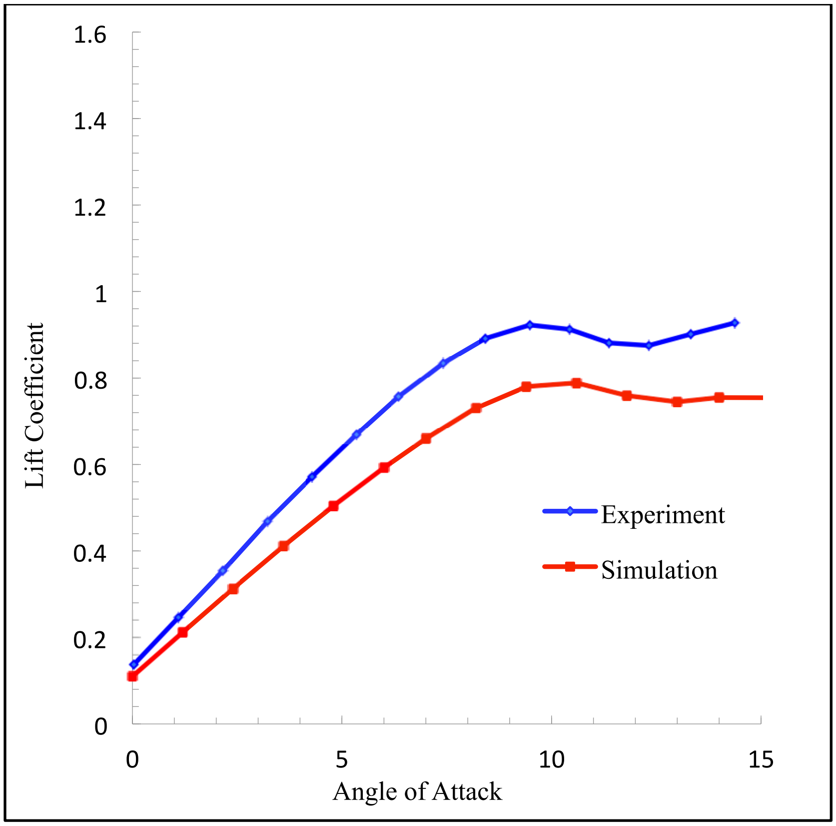

Figure 27 – Comparison of FENSAP predicted lift curve and experiment lift curve – Run B5

The experimental lift curve shows a steeper slope and a 15% higher maximum lift. Flow separation and stall occur first in the experimental curve at 9.5 degrees, and then immediately after in the FENSAP predicted curve at 10.6 degrees. As mentioned earlier, the discrepancy that exists in the evaluation of the performance degradation is likely due to the small differences in the resulting ice shape. This shows the importance of accurately replicating the ice shape, and that more ice does not necessarily mean greater performance degradation.

5.4.5. Run B6 – Intermittent Maximum: Glaze Ice

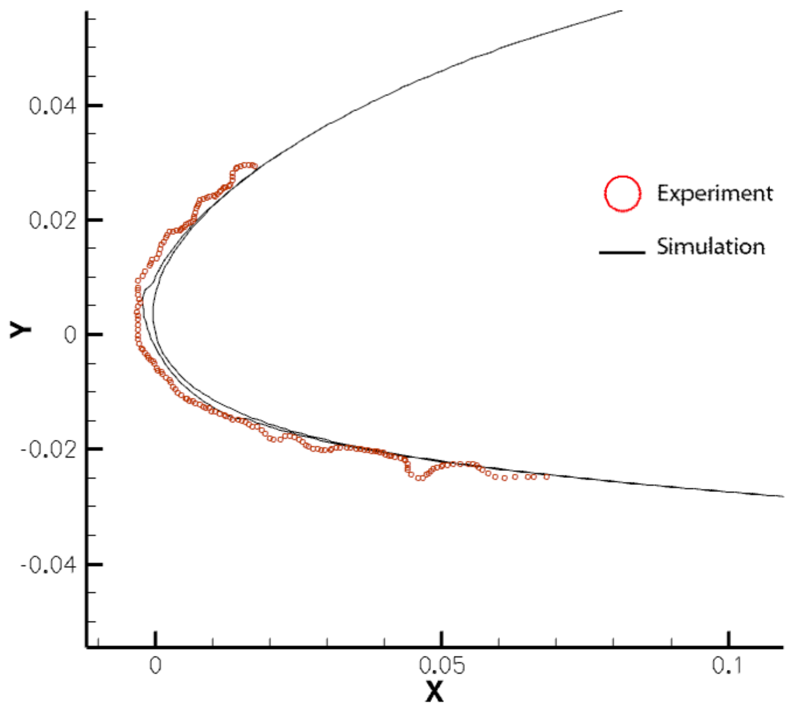

Figure 28 – Comparison of FENSAP predicted ice shape and IWT ice shape – Run B6

In figure 28, the ice shape predicted by FENSAP is slightly thinner and smoother than the experimental shape. However, the maximum thickness is captured, as are the impingement limits at the leading edge and on the upper surface. Some irregularities are noted on the lower surface, where undulations in the experimental ice shapes are not captured. This run is also excluded from LPTP testing and thus no comparison for the performance degradation is available.

6. Computational Fluid Dynamics for Certification

How can we be more proactive in our approach to managing in-flight icing?

Based on the conclusions of the accident data analysis, specific sets of conditions are found to be common to most accidents. Combining this accident information and the analysis of current trends in global air transport development with the world surface temperature and precipitation distribution provided by ArcGIS, one can identify areas that will be susceptible to in-flight icing. A detailed method of analyzing the exposure to risk of specific aircraft in these areas can then be developed using area meteorological reports and computational fluid dynamics icing predictions.

The information from local meteorological forecasts such as temperature and probability of encountering precipitation is combined with the information gleaned from CFD-Icing simulations in order to design an aircraft specific risk assessment for different areas. In particular, this risk management framework could be applied to high-risk areas or regions that have similar meteorological conditions to current icing hotspots and are showing an increasing trend in air traffic. Several occurrences from current areas with higher icing accident rates are simulated in FENSAP-ICE with the same de-icing boot performance profiles used in the previous validation section. Details for the simulations are taken from the factual accident reports provided by the National Transportation Safety Board (NTSB) in the United States. These simulations are run to demonstrate how the developed safety risks management system functions and to establish how CFD can be used as a predictive tool in identifying hazardous conditions for specific aircraft types. Conditions may lie within the Appendix C curves, and are not particularly hazardous for some aircraft, but can pose a significant threat to others, especially in the case of freezing rain. Such freezing precipitation is known to occur more frequently in climates like those of the Great-Lakes and Newfoundland [38], which have expectedly been identified as higher hazard regions.

6.1. Safety Risk Management Analysis

Handling the predictive information in a consistent and efficient way

In order to evaluate the level of risk involved, some measurable quantities known as performance metrics must be identified. The three metrics that are chosen to evaluate the performance degradation of the aircraft are: the percent reduction in maximum lift, the reduction in slope of the lift curve and finally, the reduction in stall angle. The reduction in maximum lift constitutes a measure of the magnitude of the overall performance penalty, whereas the change in slope reflects the incremental penalty that is expected to be experienced as a maneuver is performed. The drop in stall angle is an indication of the level of vigilance that is required to avoid incidents. In other words, if the aircraft is flying with contaminated surfaces, the reduction in stall angle is a measure of how sudden the onset of stall will be, and whether or not the pilot will benefit from a timely stall warning alert.

A safety risk is defined in the ICAO Safety Management Manual[39] as “the assessment, expressed in terms of predicted probability and severity, of the consequences of a hazard, taking as reference the worst foreseeable situation”. The safety risk severity table below summarizes how the metrics are determined to impact the gravity of the occurrence. The results from flight tests conducted by the FAA [9] are used to relate quantifiable information such as lift reduction and stall angle changes to some of the qualitative handling characteristics of the aircraft. The proposed severity evaluation can be complemented with the icing reporting mechanism developed by Jeck [12], where the effect of icing on the aircraft is considered as a basis for the measure of icing intensity.

Table 3 – Safety risk severity table

Severity of Occurrence	Meaning	Value
Catastrophic	Maximum lift loss in excess of 40% Reduction in slope of lift curve over 30% Stall angle reduction of greater than 5 degrees Unable to maintain altitude & control of aircraft exceedingly difficult Control impossible	A
Hazardous	Maximum lift loss on the order of 30% Reduction in slope of lift curve over 20% Stall angle reduction of 4 degrees followed by rapid decrease in lift Unable to maintain altitude & stall warning ineffective Aircraft may exhibit unusual control behavior	B
Major	Maximum lift loss on the order of 20% Reduction in slope of lift curve over 10% Stall angle reduction of 4 degrees followed by smooth decrease in lift Unable to climb above weather & moderate buffeting experienced	C
Minor	Maximum lift loss on the order of 10% Reduction in slope of lift curve over 5% Stall angle reduction of 3 degrees followed by sudden decrease in lift Climb rate diminished & aircraft may exhibit unusual control behavior	D
Negligible	Maximum lift loss on the order of 10% Stall angle reduction of 2 degrees Climb rate diminished & aircraft control unaffected	E

As part of the risk management process, it is important to perform an assessment of the tolerability of a given situation based on the probability and consequences of encountering the hazard. Table 4 below gives the probability scale for an occurrence. This information can be derived from meteorological forecasts available to pilots and air traffic controllers pre-flight.

Table 4 – Safety risk probability table

	Meaning	Value
Frequent	Likely to occur continuously	5
Occasional	Likely to occur sometimes (intermittent)	4
Remote	Unlikely to occur, but possible	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely Improbable	Almost inconceivable that the event will occur	1

From these tables, a risk matrix (see table 5) is created to assess the tolerability of the hazard. The combinations that are flagged in red indicate that these conditions require extreme caution and great effort should be made to avoid exposure either by delaying departure or re-routing the flight. Should the flight proceed into icing conditions, the pilot should review the operating limitations of the aircraft as well as the procedures for exiting icing conditions. Meanwhile, conditions that fall under the yellow classification also demand caution; operators should be more vigilant to the hazard, review the icing operations procedures and be aware of the potential consequences of flying with ice. The scenarios that are deemed low risk are flagged in green, and while extra precaution may not be necessary, the process of evaluating the risk would have increased the crew's awareness to the potential hazard.

Table 5 – Safety risk assessment matrix

	Catastrophic	Hazardous	Major	Minor	Negligible
Frequent	5A	5B	5C	5D	5E
Occasional	4A	4B	4C	4D	4E
Remote	3A	3B	3C	3D	3E
Improbable	2A	2B	2C	2D	2E
Extremely Improbable	1A	1B	1C	1D	1E

This methodology can be used to determine the tolerability of the hazard, in particular for the regions that have been identified as being at risk for icing related incidents. In addition to increasing awareness of icing occurrences, this methodology provides the users with, at the very least, a relevant qualitative measure of the consequences of the aircraft's exposure to specific icing conditions. Thus, with the results of this analysis, the operator can develop adequate risk mitigation strategies.

The importance of developing awareness cannot be understated. Over the years, improvements have made aircraft much safer, and have greatly reduced the number of accidents caused by faulty design and mechanical breakdown. Human caused errors on the other hand have risen proportionally [1], and thus accident prevention methods should focus on enabling the human side of aviation to make better decisions.

6.2. Recreating Accidents

Demonstrating the safety management system through accident analysis.

Several accidents are recreated to illustrate how this methodology can be applied to realistic operational situations. The general flight conditions are described and then simulated via FENSAP-ICE to compare the computed ice thickness with the information available in the accident report. The aerodynamic performance of the contaminated airfoil is compared with that of the clean airfoil to show the amount of degradation. The performance is also compared to the behavior of the aircraft at the time of the incident, available either through commentary from the pilot, radar observations or from witnesses on the ground, as documented by the

National Transportation Safety Board (NTSB) in the accident factual report. The accidents that are simulated all involve aircraft designed with NACA 23012 airfoil sections.

In each case the conditions are characterized by their ground temperature and assumed temperature at altitude, airspeed, assumed pitch angle, altitude, and an estimate of exposure time, made based on the sequence of events provided in the accident report. Each accident has a figure indicating the location of the simulated conditions within the Appendix C envelope for continuous maximum exposure. This is followed by a figure of the predicted ice shape, as well as the lift curve associated with the contaminated airfoil.

6.2.1. Accident 1 [40]

Ground Temperature: 30.2 °F
Temperature – At altitude: 21.2 °F
Airspeed: 200 mph
Pitch Angle: 0 degrees
Altitude: 4000 feet
Assumed time in icing: 11 minutes

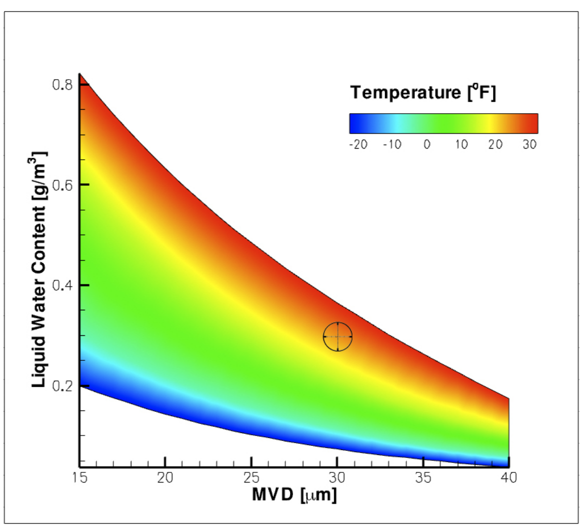

Figure 29 – Location of Accident 1 in Appendix C envelope

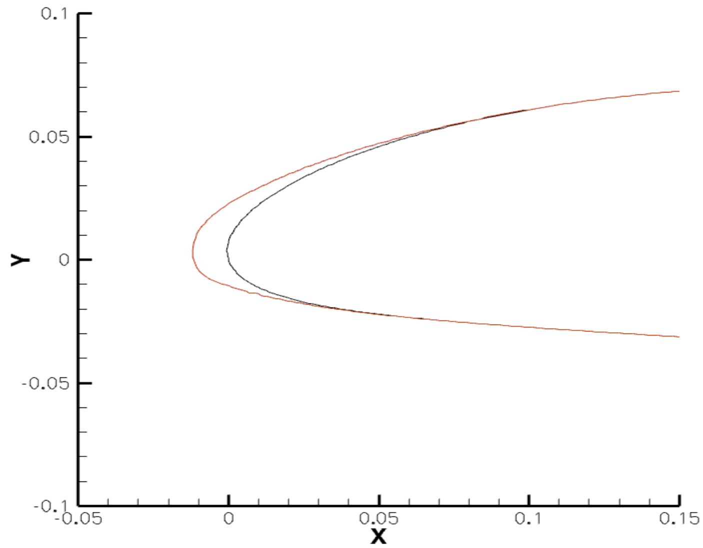

Figure 30 – Ice shape predicted by CFD-Icing simulation for Accident 1

In this case, the weather and pilot information reports clearly indicate that the aircraft could expect to encounter icing conditions and precipitation between 3,000 and 14,000 feet. Inspection of the wreckage revealed the presence of pieces of ice greater than one inch thick that "had a semicircular shaped edged that was consistent with a leading edge of an airfoil" [40]. The 0.89-inch accumulation predicted by the FENSAP-ICE analysis in figure 30 matches these observations. The measurement of thickness is scaled by a factor of 1.7 to account for differences in chord length from the tip to root of the wing [41] . The resulting lift curve can be seen in figure 31.

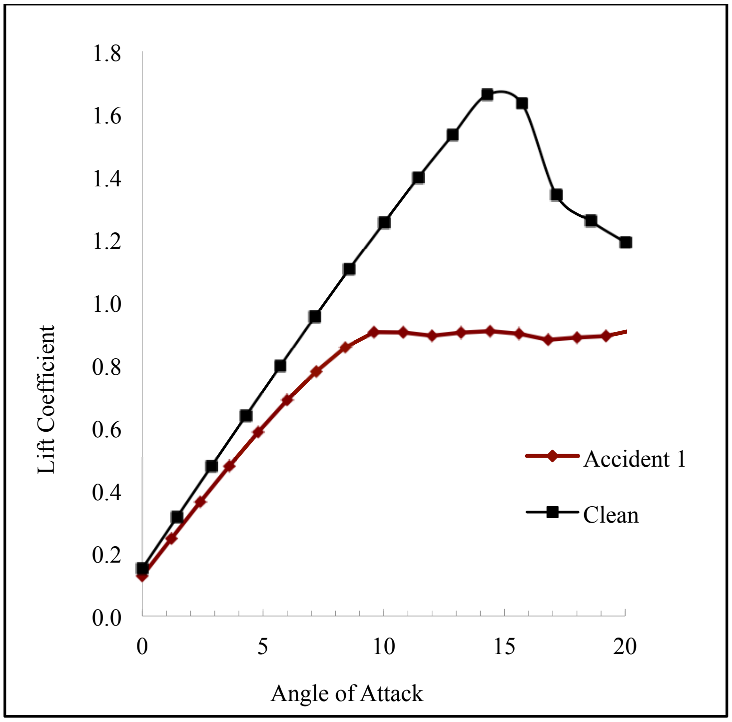

Figure 31 – Lift curve of ice shape for Accident 1 compared to clean lift curve

The simulation for a range of angles of attack shows a decrease in maximum lift on the order of 40%, and a reduction in the slope of the lift curve of over 20%. Looking at the lift reduction in the operational area of 10 degrees angle of attack the lift coefficient is reduced by 27%. Furthermore, the stall angle for the contaminated airfoil is over 5 degrees sooner than for that of a clean airfoil. The predicted performance degradation is verified with information from the cockpit voice recorder where the pilot stated that he was no longer able to maintain altitude. One can infer from the comments that the performance degradation was gradual and that control of the aircraft was becoming increasingly difficult as the pilot struggled to maintain altitude.

As mentioned earlier, the weather information available prior to departure indicated that occasional severe icing conditions were to be expected between

3000 and 14000 feet at the time of flight [40]. Based on the risk assessment process developed in the previous section, this scenario would be classified as 4A in table 5, Occasional-Catastrophic exposure, and should be avoided. While air traffic control provided the necessary information to conclude that the conditions were perilous, the decision to proceed with flight remains in the hands of the pilot and the operator. The ambiguity of the regulations no doubt played a role in this accident, as it is permissible to take off into known or forecast severe icing conditions according to 14CFR § 135.227, if the aircraft is certified for flight into icing conditions as per section 34 of Appendix A to Section 135. However, it is obvious from this analysis and from the very definition of severe icing that proceeding with flight in such conditions is dangerous.

6.2.2. Accident 2 [42]

Ground Temperature: 30.2 °F
Temperature – At altitude: 21.2°F
Airspeed: 200 mph
Pitch Angle: 4 degrees
Altitude: 6000 feet
Assumed time in icing: 3 minutes

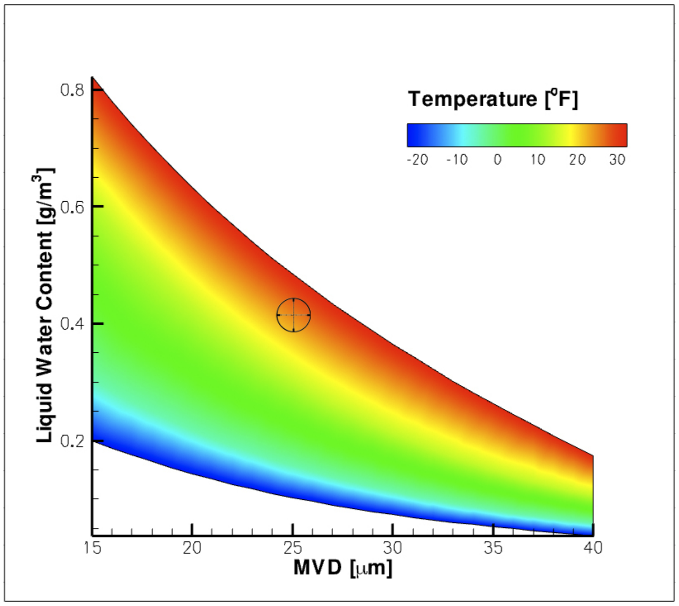

Figure 32 – Location of Accident 2 in Appendix C envelope

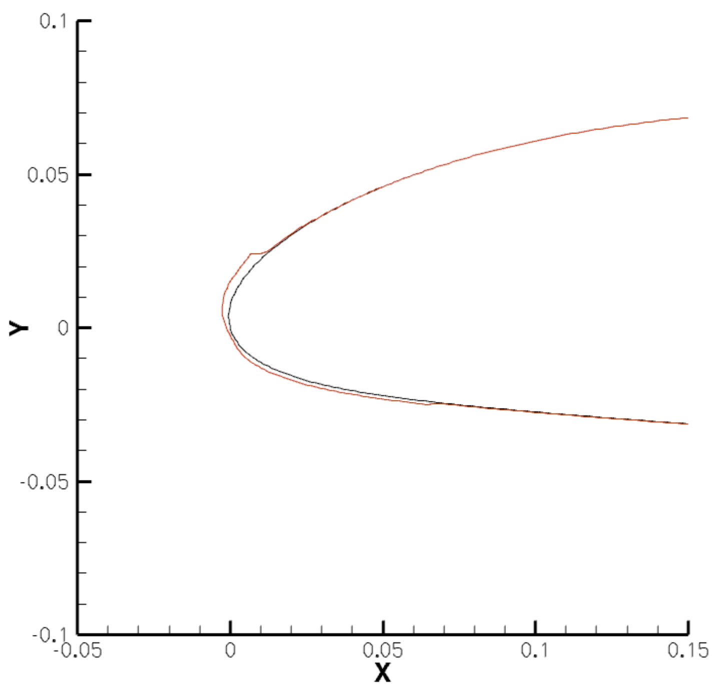

Figure 33 – Ice shape predicted by CFD-Icing simulation for Accident 2

In this scenario the exposure time to icing was short, and yet the consequences were very severe. The pilot noticed that approximately 0.25 inch of ice had accreted early on in flight, and was cleared by air traffic control to increase his altitude in an effort to escape the icing conditions. While the aircraft was no longer accreting ice, the little that he had accreted caused severe degradation of the aerodynamic performance of the aircraft. The ice shape predicted by simulating the meteorological conditions at the time of takeoff in FENSAP-ICE yielded a maximum thickness of 0.27 inches as shown in figure 33, consistent with observations made by other pilots flying in the area at the time of the incident.

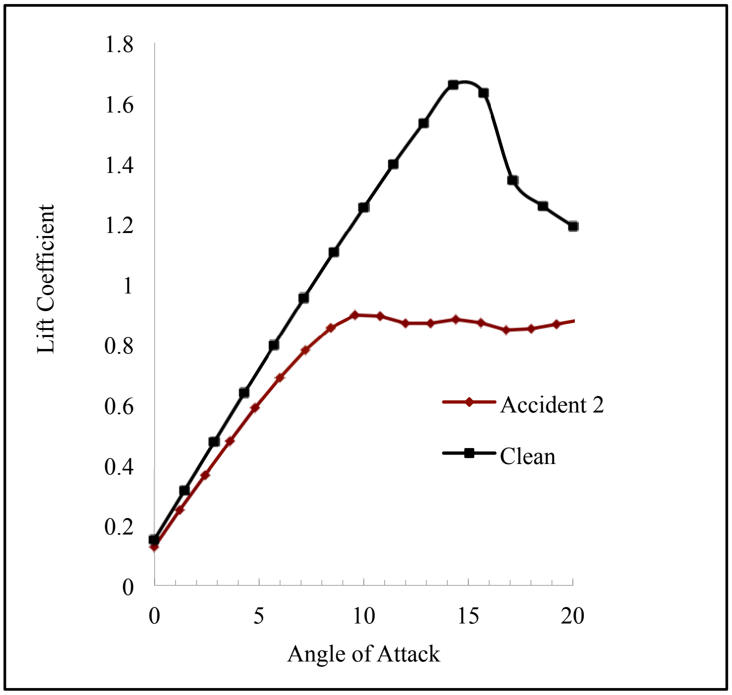

Figure 34 – Lift curve of ice shape for Accident 2 compared to clean lift curve

The lift curve in figure 34 shows the substantial decreased performance that could be expected with the small, but rough ice accretion after only 3 minutes. The maximum lift is reduced by over 40%, with the slope of the lift curve being 30% less than the clean curve indicating that the plane can also expect some significant performance penalties at lower angles of attack, prior to reaching the stall angle. The implications of the decreased stall angle and slope of the lift curve are that as the aircraft reduces its velocity for approach it simultaneously would extend the flaps to increase the angle of attack and maintain adequate lift. However if the ensuing angle of attack exceeded the stall angle, flow separation would occur and the aircraft would stall.

The weather report indicated freezing temperatures, high humidity and overcast ceilings at 400 feet all around the destination aerodrome. The classification of this scenario according to the risk assessment technique is Occasional-Catastrophic (4A). The decision to fly should be taken with caution, and the emergency procedures should be reviewed.

6.2.3. Accident 3 [43]

Ground Temperature: 28.4°F
Temperature – At altitude: 19.4°F
Airspeed: 150 mph
Pitch Angle: 4 degrees
Altitude: 3100 feet
Assumed time in icing: 6 minutes

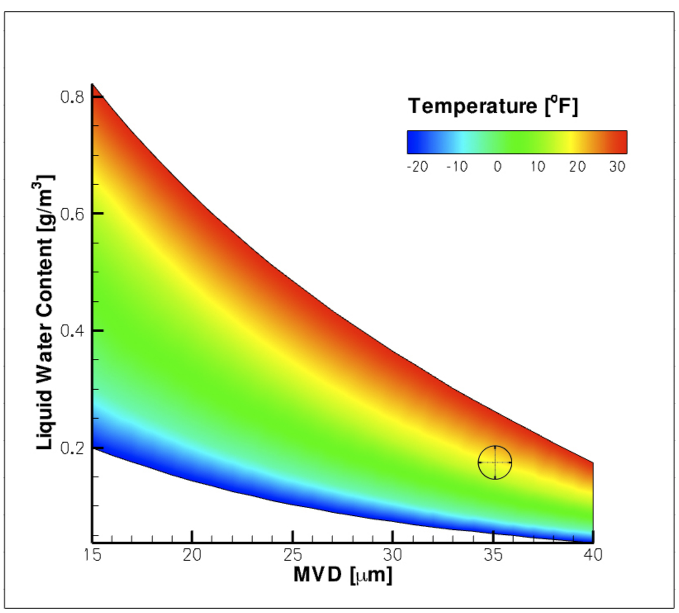

Figure 35 – Location of Accident 3 in Appendix C envelope

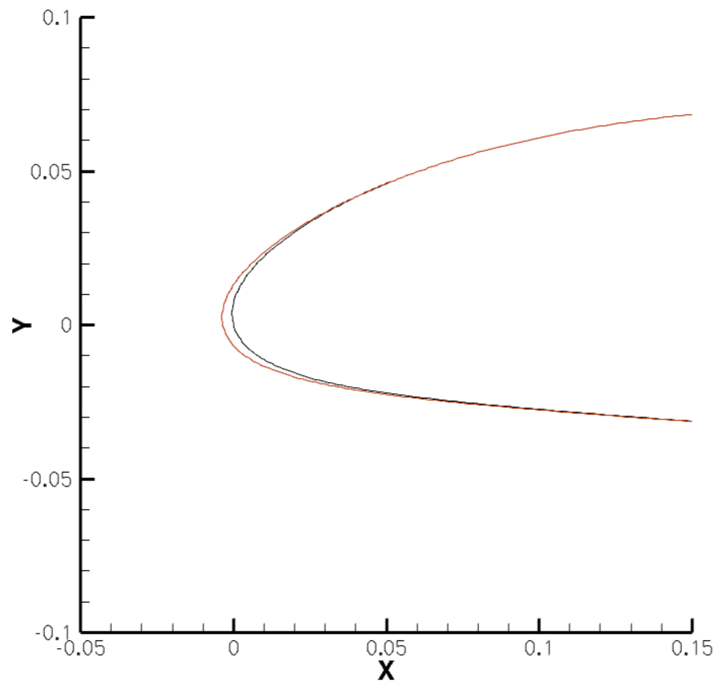

Figure 36 – Ice shape predicted by CFD-Icing simulation for Accident 3

This incident occurred just after a missed approach, as the aircraft was preparing to gain altitude again. According to the accident report, the pilots were unaware of the ice that had accumulated on the leading edge of the wings. Two witnesses, at the scene of the accident reported that they observed 0.25 inch of ice accumulation on the leading edge of the wing. This is adequately replicated in the numerical simulation (Fig. 36), which predicts an accumulation of 0.27 inches.

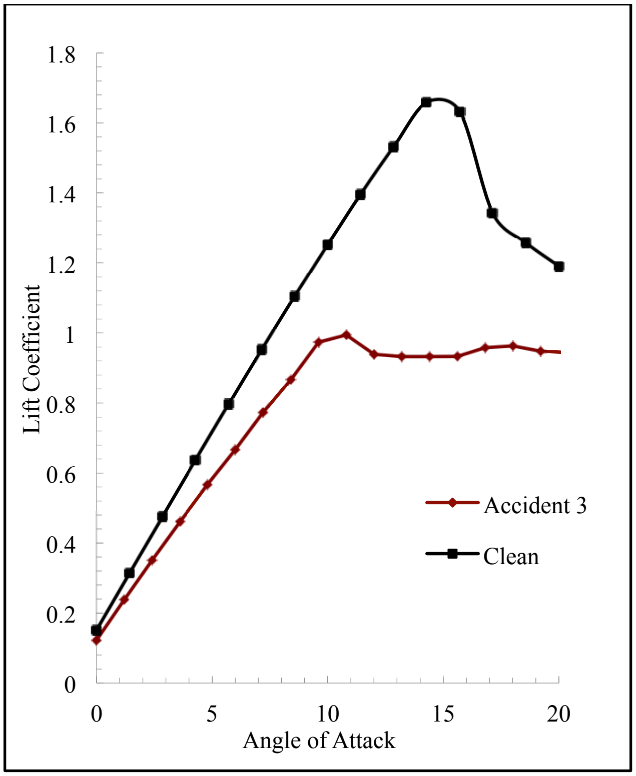

Figure 37 – Lift curve of ice shape for Accident 3 compared to clean lift curve

Despite the adverse weather forecast that clearly included freezing temperatures and overcast skies, there was a lack of awareness of the hazard that was present. In fact, from the FAA's Airport surveillance radar, it became clear that the pilots, while climbing, decreased the airspeed below the recommended minimum airspeed for flight in icing conditions. The lift curve in figure 37 shows that stall angle is reduced to approximately 11 degrees, an angle which is consistent with maneuvering out of a climb. The reduction in lift coefficient at this angle is on the order of 30% and the slope of the lift curve is also reduced by 28%. The problem is further exacerbated by the pilot's decision to reduce speed, which undoubtedly triggered a stall. This was confirmed by witnesses who reported the aircraft's wings banking left and right before descending rapidly and impacting the ground.

This scenario ranks as a Remote-Hazardous (3B), one that would require increased vigilance and situational awareness. An accident investigation report, involving the same aircraft in similar conditions revealed that the iced aircraft can "experience a decrease in the vertical acceleration and a slight decrease in the airplane pitch angle consistent with significant flow separation over the wings and the initiation of an aerodynamic stall. Calculation of the angle of attack indicated that it was about 9 degrees at the time of the upset. Additionally, the sound of the stall warning horn was not heard […]."[43] The simulation results are consistent with these observations, as the stall would occur before the stall warning system had been designed to alert the pilot.

There is little doubt that this incident could have been avoided if the recommendations found in the pilot operating handbook's Known Icing Equipment Supplement, to maintain extra airspeed in icing conditions had been followed. In addition, one should note that recommendations made subsequently by the FAA through Airworthiness Directive (AD) 2007-10-15 to install a low airspeed awareness system would have helped prevent this occurrence. The risk assessment would have made the pilots aware of the precarious situation that they were flying in, and would have suggested a review of the icing operations procedures prior to flight. Moreover, the risk assessment could be used to justify requiring the installation of airspeed awareness systems that consider ice contamination.

6.2.4. Accident 4 [44]

Ground Temperature: 15.8°F
Temperature – At altitude: 15.8°F
Airspeed: 180 mph
Pitch Angle: 4 degrees
Altitude: 600 feet
Assumed time in icing: 10 minutes

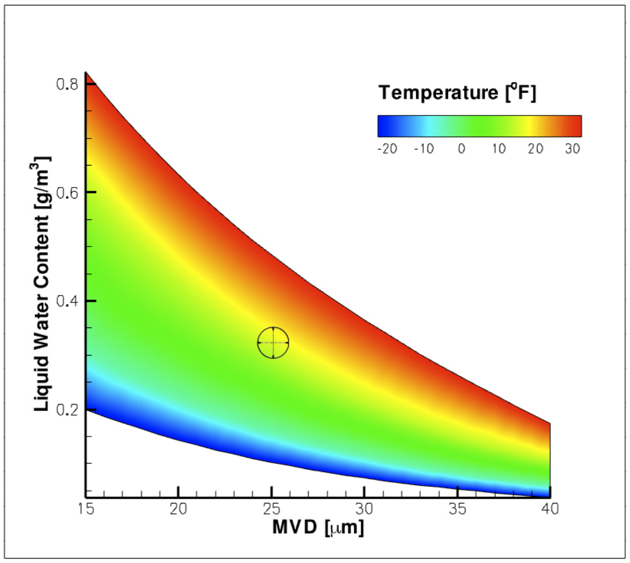

Figure 38 – Location of Accident 4 in Appendix C envelope

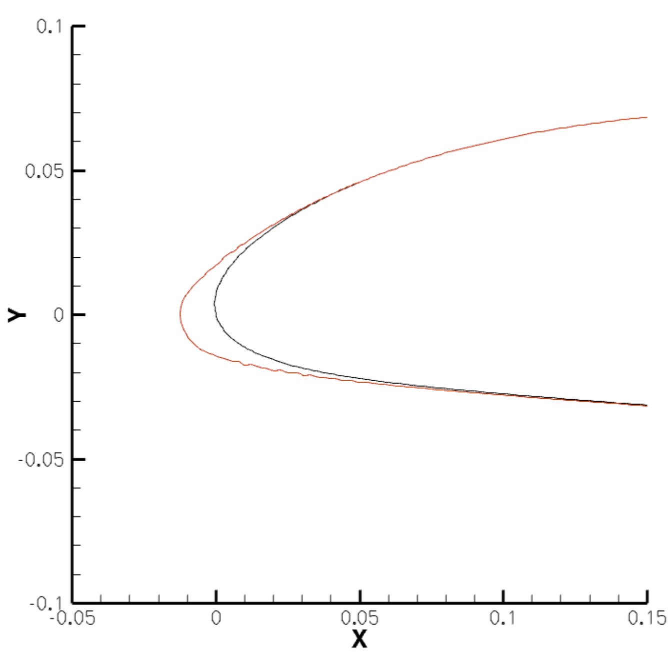

Figure 39 – Ice shape predicted by CFD-Icing simulation for Accident 4

The final accident that is simulated is similar to the previous one by the fact that the pilot was oblivious to the hazard that he was facing. The meteorological forecast that provided the data for the simulation indicated a low cloud cover along the entire route from origin to destination. This forecast was available before the flight, as was another pilot's report that indicated that his aircraft, a significantly larger DC-6, picked up what he described as light ice while on final approach. The perceived icing risk and severity is very different for a large DC-6 aircraft when compared to the smaller single engine aircraft involved in this accident. Simulating the continuous exposure yielded the smooth ice shape shown in figure 39. The predicted thickness of nearly 1 inch is slightly greater than the 0.25 to 0.5 inches of ice that was recorded in the accident report.

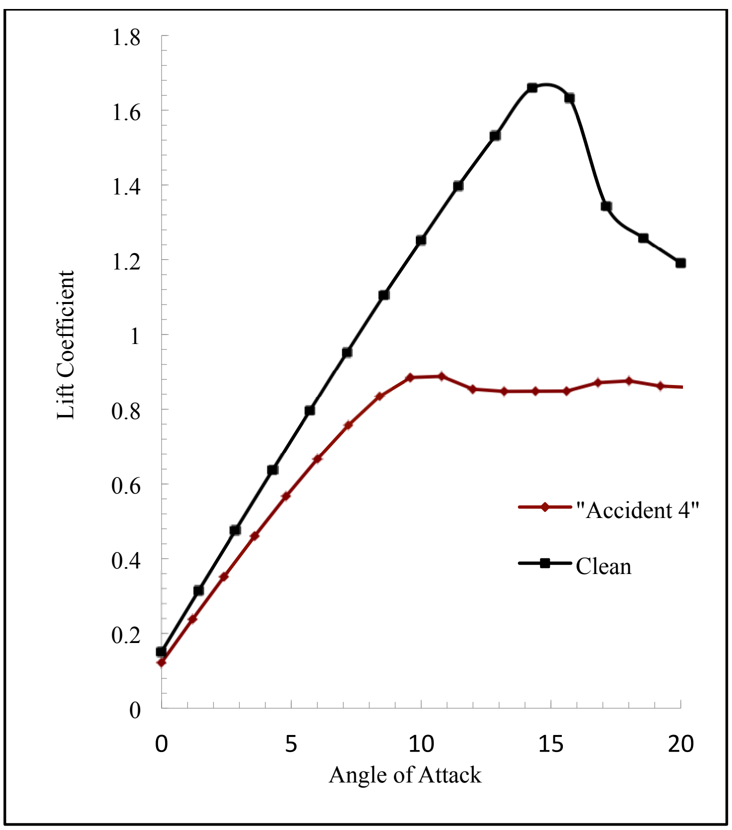

Figure 40 – Lift curve of ice shape for Accident 4 compared to clean lift curve

The above lift curve shows that the aircraft would have had trouble maintaining altitude with an incremental reduction in lift of 30%. Thus, the aircraft would have experienced severe performance degradation even at small angles of attack. The low ceilings and poor visibility caused the pilot to miss his first landing attempt, as he could not locate the aerodrome. Thus as the pilot attempted to climb back through the clouds and maneuver around to re-attempt his landing, he undoubtedly increased the angle of attack beyond the now reduced stall angle of 9.6 degrees and encountered severe degradation in the aerodynamic capabilities of the aircraft leading to uncontrolled flight into terrain.

This scenario is the worst one investigated, with continuous and nearly unavoidable exposure to very hazardous conditions. Thus applying the risk analysis methodology it is clear that this is a Frequent-Catastrophic exposure situation. If a complete risk assessment had been performed, and the information regarding aerodynamic penalties caused by icing on this aircraft reviewed prior to takeoff, steps could have been taken to avoid this fatal accident such as simply postponing the flight several hours until the forecast changed for safer conditions.

Comparing the flow solution for the stall angle of the contaminated airfoil of 9.6 degrees, we see from figure 41 that the flow has separated from the iced airfoil, whereas it remains attached for the clean one. Such flow visualization can also explain an aircraft's reduced sensitivity to controls, as it is possible to identify where the flow remains attached and is able to interact with the control surfaces.

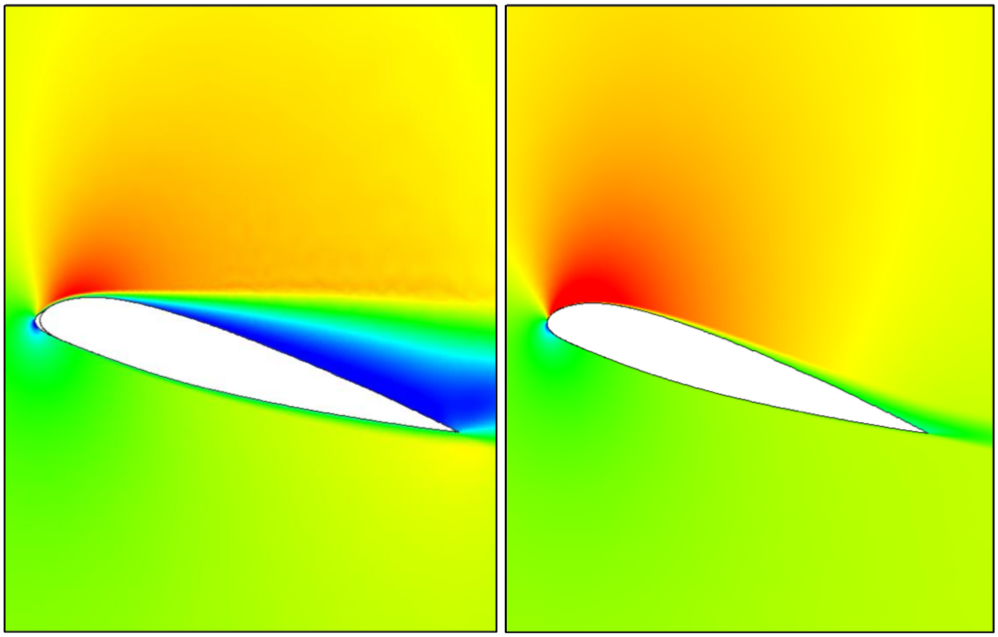

Figure 41 –Pressure contours for contaminated (left) and clean (right) airfoil at 9.6 degrees.

The level of convergence for the simulation is satisfactory for each angle. Figure 42 below shows the convergence history for four selected angles, two before the flow separates, one at the stall angle and one after flow separation has occurred.

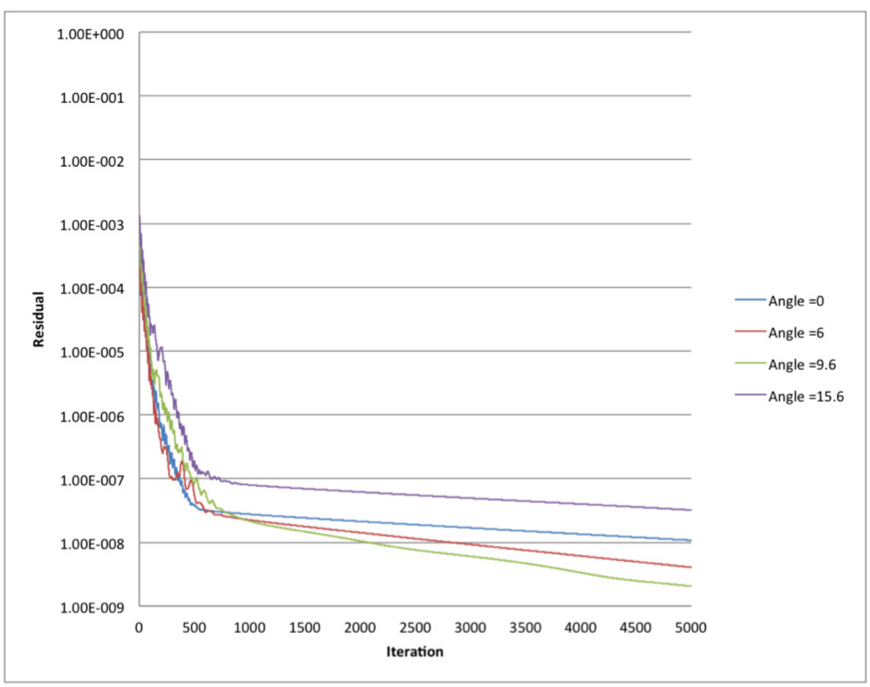

Figure 42 – Accident 4 lift curve simulation convergence for selected angles

6.3. Limitations

Despite the many positive aspects of applying CFD to predicting ice shapes and resulting performance degradation, there are some limitations to the proposed methodology that must be addressed. Firstly, as was mentioned earlier, the accuracy of the simulation code is highly dependent on the quality of the mesh [45]. In this case a single base mesh was used and updated after ice was accreted, however a single mesh is not ideal when there are changes in angle of attack or Reynolds number. Therefore it is imperative to first ensure that an optimized mesh is used for the simulations being performed to achieve more accurate results.

Second the accuracy of the turbulence model used will play an important role in the correct prediction of the ice shape. The turbulence model has a large influence on the convective heat fluxes, which in turn will impact how much ice will form in the ice accretion module: ICE3D. In addition, the advantage of higher accuracy solutions offered by the solving the viscous Navier-Stokes equations is counter-balanced by the higher costs of such solutions when compared to other CFD methods [45].

Next, there are obvious limitations to using a two-dimensional airfoil to represent a finite wing. In both cases there is a high-pressure region on the lower surface and low-pressure flow on the upper surface, however in the finite wing there is interaction between top and bottom regions. An inboard airspeed is induced on the upper surface, whereas an outboard velocity component is added to the bottom. At the wingtip railing edge the flows meet and form a vortex [23]. Trailing edge vortices cause a downward component in the air velocity to form known as the downwash and thus the real local angle of attack is changed. This will influence where the amount of ice that forms as well as where it forms along the wingspan.

There are also some elements in this methodology that may need to be improved upon such as adding the effect of ice on the drag of the airfoil to the list of performance metrics. Though drag penalties are considered secondary to maximum lift loss [30], the impact on stability and control should not be overlooked.

7. Conclusion

The accident analysis showed that there exists a concentration of in-flight icing occurrences in regions that experience high levels of traffic, coupled with higher levels of precipitation and relatively lower temperatures. In addition the analysis identified turboprop aircraft as being more susceptible to icing events, and the NACA 23012 airfoil as being most sensitive to ice contamination.

A risk assessment method was developed to offer a comprehensive approach to manage the in-flight icing hazard. Maximum lift degradation, reduction in the slope of the lift curve and change in stall angle were proposed as performance metrics to evaluate the aerodynamic consequences of ice contamination caused by specific flight conditions.

The flight conditions were simulated using the computational fluid dynamics icing system FENSAP-ICE. The results were analyzed for different angles of attack and were compared to experiments performed in the icing wind tunnel on the same airfoil. The simulation results were found to correlate very well with the experiment. Accident scenarios were then modeled based on meteorological and flight conditions at the time of the incident to predict the ice shape that would form on the airfoil and consequently the aerodynamic properties of the contaminated airfoil. The risk assessment methodology was applied to these icing scenarios and the results revealed that the consequences of icing encounters can be accurately predicted by CFD-icing simulation software such as FENSAP-ICE. These predictions are based solely on the pre-flight meteorological forecast and the known flight parameters for the aircraft involved. Despite these aircraft being certified for flight into known icing conditions, the level of safety was not maintained in part due to the sensitivity of this particular airfoil to ice contamination and in part to lapses in pilot awareness of the severity of the consequences of in-flight icing on the aircraft. The latter can be attributed to the confusing and misleading regulations regarding flight into severe icing and the overall ineptitude of the icing severity taxonomy.

When performing in-flight icing certification flight tests, scientists, engineers and pilots go to great risk to acquire the data required to certify aircraft for flight into icing conditions. The implementation of safety management to mitigate the in-flight icing risk will never replace their important work, but rather it can supplement it by identifying beforehand; “combined” conditions that aircraft equipped with de-icing boots and certified for flight into icing conditions would find difficult or impossible to handle.

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Appendix A – Current FAA Airframe Icing Reporting Table

TRACE	Ice becomes perceptible. The rate of accumulation is slightly greater than the rate of sublimation. It is not hazardous even though de-icing/anti-icing equipment is not utilized, unless encountered for an extended period of time over 1 hour.
LIGHT	The rate of accumulation may create a problem if flight is prolonged in this environment (over 1 hour). Occasional use of de-icing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the de-icing/anti-icing equipment is used.
MODERATE	The rate of accumulation is such that even short encounters become potentially hazardous and the use of de-icing/anti-icing equipment or flight diversion is necessary.
SEVERE	The rate of accumulation is such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary.

Appendix B - Creating the Numerical Tunnel

The airfoil geometry was derived from the NACA five-digit series equations:

$$y_c = \frac{k_1}{6}\left[x^3 - 3mx^2 + m^2(3-m)\;x\right] \qquad \text{from } x=0 \text{ to } x=p$$

$$y_c = \frac{k_1\;m^3}{6}(1-x) \qquad \text{from } x=p \text{ to } x=c$$

Equation 1 [1]

Where m and k_1 are defined for the 23012 in the third line of table 1 below:

Table 1 – Values of m and k1 according to mean-line designation [1]

Mean-line designation	Position of max camber (p)	m	k1
210	0.05	0.0580	361.400
220	0.10	0.1260	51.640
230	0.15	0.2025	15.957
240	0.20	0.2900	6.643
250	0.25	0.3910	3.230

The thickness distribution above and below the mean line is given by the equation below:

$$\pm\, y_t = \frac{t}{0.2}\left(0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right)$$

Equation 2 [1]

Finally the coordinates for the upper and lower surfaces are given by the following equations:

$$x_U = x - y_t\;\sin\theta$$
$$y_U = y_c + y_t\;\cos\theta$$
$$x_L = x + y_t\;\sin\theta$$
$$y_L = y_c - y_t\;\cos\theta$$
$$\text{where } \theta = \arctan\left(\frac{dy_c}{dx}\right)$$

Equation 3 [1]

These equations are then used to generate the geometry for the NACA 23012 shown below in Figure 1:

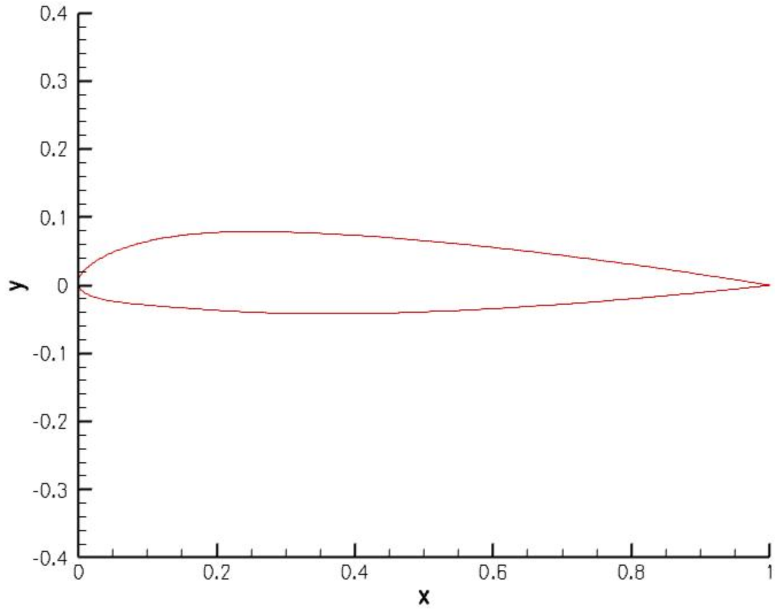

Figure 1 - NACA 23012 Airfoil Geometry

Meshing

Once the geometry is created, the surrounding fluid domain must be meshed. This is accomplished using an automated meshing tool developed by Marco Fossati at the Politecnico di Milano [2]. This tool creates a hybrid mesh, with quadrilateral elements enveloping the airfoil and triangular elements filing in the majority of the fluid domain. A hybrid mesh was chosen because it allows for controlled distribution of quadrilateral elements in regions of where large gradients occur such as in the boundary layer. Although the boundary layer region is small relative to the entire flow field, any inaccuracies in this region will impact the solution for the entire flow area. Therefore to minimize discretization errors, anisotropic elements are aligned with the flow direction and are concentrated in the boundary layer region [2].

Mesh Parameters

The hybrid mesh can be described in three distinct sections: the far field mesh, the boundary layer mesh and the wake mesh. The mesh is constrained to a fluid domain region with a radius of 35 times the chord length of the airfoil.

The outer boundary element sizes are defined at different points along the arc-length of the airfoil according to the values in table 2. The triangular element sizes between the outer limit elements and the structured elements in the boundary layer are computed using the Delaunay Triangulation.

Table 2 – Far field Element Parameters

Normalized Arc Length	Equilateral Triangle Side Length
0.0	1.0
0.1	5.0
0.5	8.0
0.9	5.0
1.0	1.0

In the boundary layer region, more details are provided to shape the elements to ensure that they are anisotropic. In this case the boundary layer is composed of 75 layers of quadrilateral elements with the element height and length growing as the distance from the airfoil increases according to the following relationships.

The height of the element is governed by

$$h_i = h_i(1+\delta)^i \qquad i = 1, Nlayer \quad \text{Equation 4 [2]}$$

Where: h_i = initial height

δ = variation parameter = 0.11

NLayer = Number of Layers = 75

The maximum length of the element is governed by

$$L_{\max} = ref.Leng * (1+Par)^i \qquad i = 1, Nlayer \quad \text{Equation 5 [2]}$$

Where: ref.Leng = Median base length of three adjacent first layer quadrilaterals

Par = variation parameter = 1.25

NLayer = Number of Layers = 75

The first layer element sizes at different points along the airfoil arc-length are defined in the following table:

Table 3 – Boundary Layer Element Parameters

Normalized Arc Length	**Quad Length**	**Quad Height**
0.00	0.0035	0.0000012
0.20	0.0060	0.0000012
0.35	0.0025	0.0000012

0.51	0.0010	0.0000003
0.65	0.0025	0.0000012
0.80	0.0060	0.0000012
1.00	0.0035	0.0000012

Finally, the grid parameters are specified for the wake region

Table 4 – Boundary Layer Element Parameters

Normalized Arc Length	**Quad Length**	**Quad Height**
0.00	0.0030	0.0000012
0.25	0.0050	0.0000150
0.50	0.0850	0.0000500
1.00	0.5000	0.0000800

The result is shown in the following three figures.

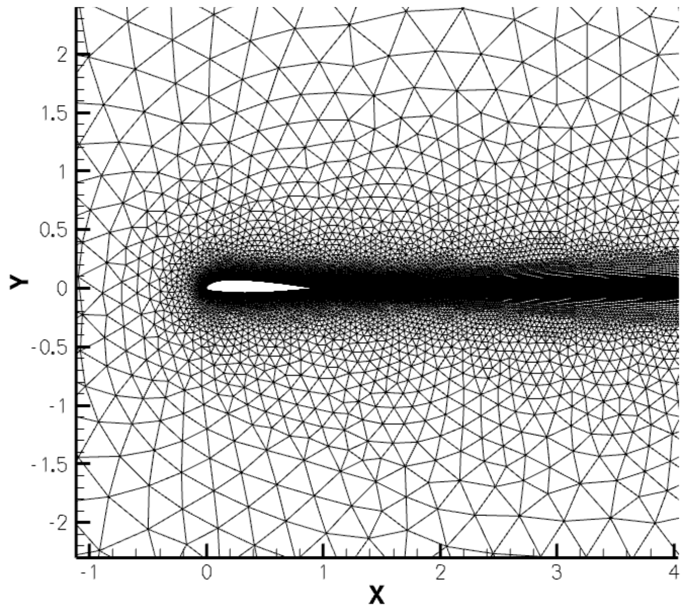

Figure 2 – Broad view of hybrid grid

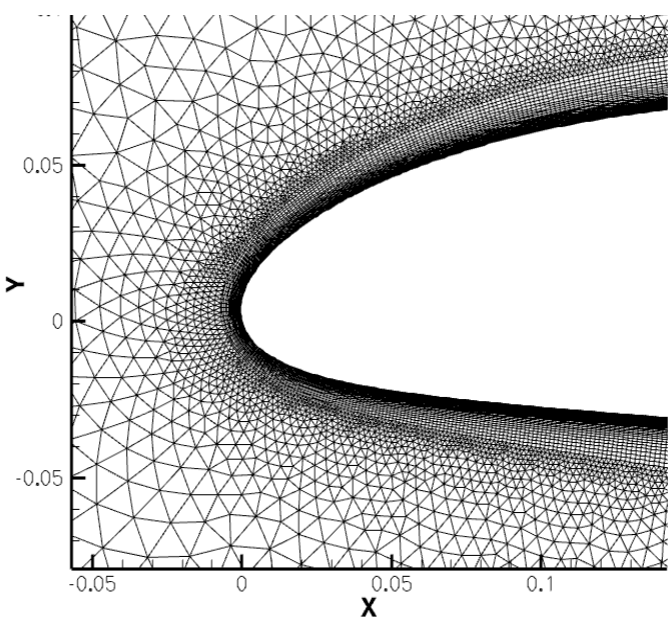

Figure 3 – Leading edge of airfoil showing the union of the unstructured and

structured grid.

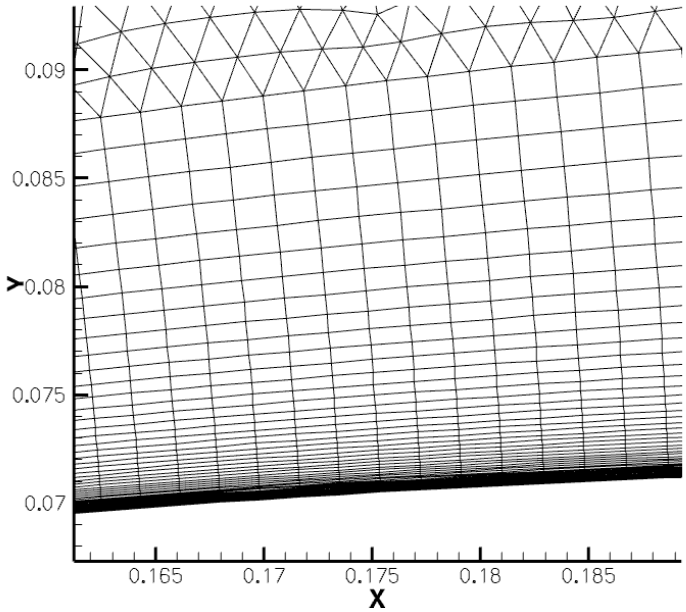

Figure 4 – View of the Expanding Structured grid in the boundary layer region around 20% chord.

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