LIQUID WATER AND FLOW TURBULANCE CHARACTERIZATION OF THE PENN STATE ICING WIND TUNNEL

A Thesis in
Aerospace Engineering

by

Ameya S Landge

© 2018 Ameya S Landge

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2018
The thesis of Ameya S Landge was reviewed and approved* by the following:

Jose L Palacios  
Assistant Professor of Aerospace Engineering  
Thesis Advisor

Dennis K McLaughlin  
Professor of Aerospace Engineering

Amy Pritchett  
Professor of Aerospace Engineering  
Head of the Department of Aerospace Engineering

*Signatures are on file in the Graduate School
Abstract

Supercooled liquid water droplets present in clouds pose a threat to safety of aircraft. The water droplets impact on the surface and freeze, distorting the shape of the airfoil. The distortion of the airfoil shape increases drag and decreases lift. An event of unsymmetrical shedding can induce vibrations. Ice accretion on fuel vents prevents regular airflow and an increase in pressure may cause the fuel sacks to implode. Ice accretion on control surfaces may change the response of the surfaces. Ice accretion to sensors such as velocity probes is also extremely dangerous. Above issues create a need for Ice Protection Systems (IPS) to be installed onboard any aircraft.

Design of Ice Protection System (IPS) is a complex iterative procedure and current modeling tools do not accurately predict the behavior of any particular system. The models can be tested in flight, on the ground and in icing wind tunnels. Inflight tests pose a risk to human life and ground icing tests may not be representative of inflight icing conditions. Icing wind tunnels are a reduced cost option to test IPS prior to mandatory flight testing for certification purposes. To ensure the data collected for IPS and icing research is accurate it is of importance to ensure certain aerodynamic parameters of the wind tunnel are within pre-established guideline limits. The goal of this research is to calibrate the liquid water content (LWC) and
flow turbulence in the vertical test section of the newly built Penn State Icing Tunnel (PSIT) for Appendix C conditions.

The calibration was performed following the guidelines and limits specified in SAE Aerospace Recommended Practices (ARP) 5905. Initially, nozzle locations were identified to give a uniform cloud in the cross-section. A uniform cloud of 11 inch by 11 inch was obtained in the center of the tunnel section. Four NASA standard nozzles are used to get the even cloud. It was demonstrated that as the speed of air increased in the cross-section the uniformity decreased from 18 inch by 18 inch to 11 inch by 11 inch. The uniformity tests were followed by LWC calibration tests. Supercooled water was sprayed only for two different airline pressures of 15 and 20 psig. For higher air pressures the water droplets froze on exiting the nozzle and fully glaciated ice crystals were obtained at location of evaluation (demonstrating the capability of the tunnel to generate both supercooled clouds and fully glaciated frozen droplets). The objective of the presented work focuses on the calibration of supercooled clouds only (14 FAR Part 25 Appendix C conditions).

Initial particle size calibration was conducted in the cross-section and further tests were carried out in the AERTS chamber to test the ability of the nozzles to produce different MVD particles sizes. Droplet sizes within and well beyond appendix C conditions were produced from 15 to 200 microns. Particle sizes below 30 microns were reproduced within ± 3 microns. Particle sizes beyond 30 microns and up to 200 microns were produced within 15 percent.
Turbulence intensity tests were conducted at three different velocities 0 m/s, 17 m/s and 34 m/s. It was found that as speed increased, the centerline turbulence intensity decreased. Speed increase from 17 m/s to 34 m/s dropped the turbulence by 31.25 percent at centerline from 3.84 percent to 2.64 percent. At 17 m/s, an average increase in turbulence intensity in the cross-section was observed of about 25 percent when air flow through the nozzle was turned on. At 34 m/s, 0.5 percent average increase was observed. The turbulence intensity on average in the cross-section is within guideline limit but certain locations have turbulence intensities higher than the limits. However, as no tests are expected to be performed so close to the walls of the cross-section, it is of little concern.

Flow angularity tests were carried out at 17 m/s. The measurement locations were limited due to length of the probe. The yaw angle was read from the protractor installed on the instrument. It has a least count of 0.2 degrees and was recorded less than 0.2 degrees at all the points. The average flow angle for the cross-section is 2.7 degrees and increased by about 13 percent to 3.05 degrees when air flow through the nozzle was turned on. The guidelines prescribe a limit of 3 degrees. As the case with turbulence intensity, some locations showed higher flow angularity but are not of grave concern.
# Table of Contents

List of Figures .................................................................................................................................................. viii
List of Tables .................................................................................................................................................... x
List of Symbols .................................................................................................................................................. xi
Acknowledgements ........................................................................................................................................... xiii
Chapter 1 .............................................................................................................................................................. 1
  1. Introduction .................................................................................................................................................. 1
    1.1 History and Development of Icing Research Tunnels over the last Century .................................................................. 4
    1.2 Thesis Objectives ....................................................................................................................................... 17
    1.3 Thesis Overview ....................................................................................................................................... 18
      1.3.1 Chapter 2: Liquid Water Content Theory .............................................................................................. 18
      1.3.2 Chapter 3: Cloud Uniformity, LWC calibration and MVD calibration .................................................... 18
      1.3.3 Chapter 4: Aerodynamic calibration ....................................................................................................... 18
      1.3.4 Chapter 5: Conclusions and Recommendations .................................................................................... 18
Chapter 2 ........................................................................................................................................................... 19
  2. Liquid Water Content Theory ......................................................................................................................... 19
    2.1 Cloud Uniformity and Liquid Water Content Calibration ........................................................................... 19
    2.2 Icing Regimes ........................................................................................................................................... 21
    2.3 Appendix C and Appendix O ................................................................................................................... 22
      2.3.1 Appendix C ......................................................................................................................................... 23
      2.3.2 Appendix O ......................................................................................................................................... 29
    2.4 LWC Calculation ....................................................................................................................................... 36
      2.4.1 Modification to the Code ....................................................................................................................... 39
        2.4.1.1 Newton Raphson Method ............................................................................................................... 39
Chapter 3 ............................................................................................................................................................. 41
  3. Cloud Uniformity and LWC Calibration ........................................................................................................ 41
    3.1 Cloud Uniformity and Liquid Water Content Calibration ........................................................................ 41
      3.1.1 Verification of results using LWEINT ................................................................................................. 56
    3.2 Median Volume Diameter ........................................................................................................................ 61
    3.3 Conclusion ............................................................................................................................................... 67
Chapter 4 ............................................................................................................................................................. 69
4. Aerodynamic Calibration ........................................................................................................69
   4.1 Turbulence Intensity ........................................................................................................69
      4.1.1 Principle of Hotwire Anemometer ............................................................................70
      4.1.2 ARP Guidelines ........................................................................................................74
      4.1.3 Results .......................................................................................................................78
      4.1.3.1 Velocity Distribution .............................................................................................78
      4.1.3.2 Turbulence Intensity .............................................................................................80
   4.2 Flow Angularity ...............................................................................................................93
      4.2.1 Results .......................................................................................................................97
   4.3 Conclusion ......................................................................................................................101
Chapter 5 Conclusion and Future Work ................................................................................102
   5.1 Conclusion ......................................................................................................................102
   5.2 Future Work ...................................................................................................................106
      5.2.1 Cloud Uniformity ......................................................................................................106
      5.2.2 LWC Improvement ..................................................................................................107
Appendix: Liquid Water Content MATLAB Prediction Code .............................................109
References ...............................................................................................................................115
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Helicopter lands after facing inflight icing [37]</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Pneumatic Icing Boots installed on the leading edge the airfoil [4]</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Goodrich icing tunnel in Uniontown, OH [8]</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Glenn IRT cross-section 6 feet X 9 feet [34]</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>RTA Icing Tunnel Schematic</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>NRC Altitude Icing Wind Tunnel [13]</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>Schematic of Penn State Icing tunnel [5]</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>(a) Glaze Ice (b) Mixed Ice (c) Rime ice [19]</td>
<td>22</td>
</tr>
<tr>
<td>11</td>
<td>Temperature and altitude extent for continuous icing envelope of Appendix C</td>
<td>24</td>
</tr>
<tr>
<td>12</td>
<td>LWC and MVD extent for continuous icing envelope of Appendix C [3]</td>
<td>25</td>
</tr>
<tr>
<td>13</td>
<td>LWC factor based on distance [3]</td>
<td>26</td>
</tr>
<tr>
<td>14</td>
<td>Temperature and altitude extent for intermittent icing envelope of Appendix C[3]</td>
<td>27</td>
</tr>
<tr>
<td>15</td>
<td>LWC and MVD for intermittent icing envelope of Appendix C [3]</td>
<td>28</td>
</tr>
<tr>
<td>16</td>
<td>LWC factor and cloud horizontal extent for intermittent icing envelope of Appendix C [3]</td>
<td>29</td>
</tr>
<tr>
<td>17</td>
<td>LWC and ambient temperature extent for freezing drizzle conditions of Appendix O [22]</td>
<td>30</td>
</tr>
<tr>
<td>18</td>
<td>MVD distribution for freezing drizzle [22]</td>
<td>31</td>
</tr>
<tr>
<td>19</td>
<td>Temperature and altitude extent of Appendix O freezing drizzle [22]</td>
<td>32</td>
</tr>
<tr>
<td>20</td>
<td>LWC and temperature extent of Appendix O in freezing rain [22]</td>
<td>33</td>
</tr>
<tr>
<td>21</td>
<td>MVD distribution in freezing rain condition for Appendix O [22]</td>
<td>34</td>
</tr>
<tr>
<td>22</td>
<td>Temperature and altitude extent for freezing rain [22]</td>
<td>35</td>
</tr>
<tr>
<td>23</td>
<td>LWC factor for Appendix O based on horizontal extent [22]</td>
<td>36</td>
</tr>
<tr>
<td>24</td>
<td>Ice thickness measurement in NASA Glenn IRT [27]</td>
<td>44</td>
</tr>
<tr>
<td>25</td>
<td>Spray system schematic in PSIT</td>
<td>46</td>
</tr>
<tr>
<td>26</td>
<td>Spraybar cylinder with heaters installed inside</td>
<td>47</td>
</tr>
<tr>
<td>27</td>
<td>Mesh used for icing and uniformity tests</td>
<td>48</td>
</tr>
<tr>
<td>28</td>
<td>Mesh close to turning vanes</td>
<td>49</td>
</tr>
<tr>
<td>29</td>
<td>Initial spray location for nozzles</td>
<td>50</td>
</tr>
<tr>
<td>30</td>
<td>Mesh on a 9&quot; stand in the cross-section</td>
<td>51</td>
</tr>
<tr>
<td>31</td>
<td>Mesh on the stand</td>
<td>52</td>
</tr>
<tr>
<td>32</td>
<td>Graph of distribution of cloud in the cross-section</td>
<td>53</td>
</tr>
<tr>
<td>33</td>
<td>Schematic for change in cloud uniformity from 0 m/s to 15 m/s</td>
<td>54</td>
</tr>
<tr>
<td>34</td>
<td>Schematic for change in uniformity from 30 m/s to 50 m/s</td>
<td>54</td>
</tr>
<tr>
<td>35</td>
<td>Normalized ice thickness for LWC 2 g/m³</td>
<td>60</td>
</tr>
<tr>
<td>36</td>
<td>Droplet size calibration curves for Standard nozzles</td>
<td>64</td>
</tr>
</tbody>
</table>
Figure 37 Droplet size calibration curves for Mod-I nozzles ........................................... 65
Figure 38 Microtrac - Aerotrac particle sizing instrument in AERTS Chamber ........ 66
Figure 39 Microtrac- Aerotrac in the test section ................................................................. 67
Figure 40 Plot of target MVD v/s measured MVD .............................................................. 68
Figure 41 One, two and three-dimensional hotwire probes [31] ..................................... 71
Figure 42 Film type wire used in the calibration ................................................................. 72
Figure 43 Hotwire probe and RTD ....................................................................................... 74
Figure 44 Turbulence Intensity measurement locations ....................................................... 75
Figure 45 Velocity distribution at 17 m/s ........................................................................... 79
Figure 46 Velocity distribution at 34 m/s ........................................................................... 80
Figure 47 Turbulence intensity distribution with 0 m/s velocity and nozzle air OFF ...... 82
Figure 48 Turbulence intensities at 0 m/s and nozzle air OFF .......................................... 83
Figure 49 Turbulence intensity distribution 0 m/s and nozzle air ON ............................. 83
Figure 50 Turbulence intensities at 0 m/s and nozzle air ON .......................................... 84
Figure 51 Turbulence intensity distribution at 17 m/s and nozzle air OFF ................... 85
Figure 52 Turbulence intensities at 17 m/s and nozzle air OFF ........................................ 86
Figure 53 Turbulence intensity distribution at 17 m/s and nozzle air ON ................... 87
Figure 54 Turbulence intensities at 17 m/s and nozzle air ON ........................................ 88
Figure 55 Turbulence intensity distribution at 34 m/s and nozzle air OFF ................... 89
Figure 56 Turbulence intensities at 34 m/s and nozzle air OFF ........................................ 90
Figure 57 Turbulence intensity distribution at 34 m/s and nozzle air ON ................... 91
Figure 58 Turbulence intensities with 34 m/s and nozzle air ON ..................................... 92
Figure 59 Five hole angularity probe .................................................................................. 93
Figure 60 Holes on five-hole probe .................................................................................... 94
Figure 61 Calibration curve for five-hole probe ................................................................. 96
Figure 62 Locations of flow angularity measurements .................................................... 97
Figure 63 Flow angularity distribution with air OFF ........................................................ 98
Figure 64 Flow angularity with air OFF .............................................................................. 99
Figure 65 Flow angularity distribution with air ON ............................................................ 100
Figure 66 Flow angularity with air ON .............................................................................. 101
Figure 67 Schematic of uniform cloud in the test section ................................................. 103
Figure 68 Intermittent conditions covered [3] ................................................................. 104
Figure 69 Extension of cloud conditions using MOD – I nozzles [3] ......................... 107
List of Tables

Table 1 Normalized ice thickness predicted by multiplying by a factor for 2 g/m³ .......... 58
Table 2 Normalized ice thickness predicted by additional repetitions for 2 g/m³ .......... 59
Table 3 Normalized Thickness predicted for 1 g/m³ ................................................. 60
Table 4 Minimum Aerodynamic test matrix [24] .......................................................... 75
Table 5 Performance targets for Turbulence Intensity Tests ........................................ 78
Table 6 Turbulence intensity test matrix for calibration tests ........................................ 81
Table 7 Performance target for flow angularity in test section ....................................... 95
Table 8 Flow angularity test matrix ................................................................................ 97
List of Symbols

Ac  Accumulation parameter (dimensionless)
b  relative heat factor (dimensionless)
Cp  Constant pressure specific heat
C_{p,ws}  Specific heat of water on model surface
d  Cylinder diameter (inch)
Eb  Collection efficiency (dimensionless)
H  Horizontal extent of clouds (nautical miles)
h_c  Convective heat transfer coefficient
h_g  gas phase mass transfer coefficient
K  Inertia parameter (dimensionless)
K_0  Modified inertia parameter (dimensionless)
K_1  Constant varies on units used (dimensionless)
LWC  Liquid Water Content (g/m^3)
n_a  Analytical freezing fraction (dimensionless)
n_e  Experimental freezing fraction (dimensionless)
Nu  Nusselt number (dimensionless)
Pr  Prandtl number (dimensionless)
P_{st}  Static pressure (pa)
P_{tot}  Total pressure (pa)
P_w  Water pressure (pa)
P_{ww}  vapor pressure of water over liquid water (pa)
Re_\delta  Droplet Reynolds number (dimensionless)
S  LWC factor (dimensionless)
Sc  Schmidt number (dimensionless)
t_s  Surface temperature (degree Celsius)
t_{st}  Static temperature (degree Celsius)
t_{tot}  Total temperature (degree Celsius)
V  Velocity (m/s)
\Delta  Ice thickness accreted (in)
Λ
Latent heat of freezing (kJ/kg)

β₀
Stagnation collection efficiency (dimensionless)

θ
Air energy transfer parameter (R)

λ_{stokes}
Drop range applying stokes law (ft)

λ
Drop range (ft)

μ
Viscosity (lbm/ft s)

ρ_{ice}
Density of ice (kg/m³)

ρ_{water}
Density of water (kg/m³)

τ
Time (sec)

φ
Drop energy transfer parameter (R)
Acknowledgements

I would like to thank my advisor, Dr. Palacios for his support and guidance. His expertise in experimentation and his attitude towards work has always been a source of inspiration for me. The platform he provided helped me become a better engineer and a better person. My special thanks to Richard Auhl who taught me apart from technical things the virtue of patience and calm mind required to conduct research and process data. I would also like to thank Sihong Yan for all his help in explaining concepts and setting up experiments. Without his help I would’ve taken much longer to finish the research work.

I would like to extend my gratitude to my colleagues, Grant Schneeberger, Belen Veras-Alba, Edward Rocco, Ahmad Haidar, Miguel Alvarez, Tirth Patel, Rebekah Douglass Raja Akif, and David Getz. Your help, support and recommendations went a long way to complete the research work.

Last but not the least, I would like to thank my family and friends for their support, guidance and providing me the necessary resources and opportunities that put me where I am today.
Chapter 1

1. Introduction

With the advent of instrument flights, aviators started flying through atmospheric conditions of clouds their predecessors circumvented due to lack of visual references. It was required for maintenance of scheduled operations of the US Air Mail Services. That is when the earliest encounter between aviators and icing was recorded, in the mid nineteen twenties while flying between New York and Chicago. Icing was regarded by the said pilots as “The greatest of our problems”. Since then aircraft icing has done away with countless lives. Thanks to certain men with vision, who continued research in aircraft and rotorcraft icing when many other contemporary researchers declared prematurely and erroneously that icing was a problem of past, research has been continued in this field [1].

Present day rotorcrafts, compared to fixed wing aircrafts are at a higher risk of encountering icing conditions, since fixed wing crafts go through such situations only during landing or takeoff while rotorcraft have a cruising altitude of 8,000 feet, where icing clouds are most frequently encountered. Once an icing condition is detected / expected, the fixed wing aircrafts can avoid the weather by flying over the clouds. Icing clouds do not consist of ice particles rather they have supercooled liquid water that freezes on impact with the structure/blade. At higher altitudes, beyond 30,000 feet, the probability of finding supercooled water is greatly reduced, Water at such altitudes exist as fully glaciated ice particles. Hence the problem of
structural icing is averted when fixed wing aircrafts fly over the clouds. However, the ice crystals create a different problem. The ice crystals get ingested into the engine and melt partially. The partially melted ice then accretes inside the engine and results into loss of thrust known as rollback [2].

From sea level up to 30,000 feet, clouds contain significant amount of supercooled water up to about 3 g/m³ [3]. Near or below freezing temperatures, this supercooled liquid water accretes on the wings, blades, ailerons, pitot tubes etc. when an aircraft travels through the cloud. Ice accreted on blade changes the shape of the airfoil, increases the surface roughness of the blades which significantly alters the lift drag characteristics of the airfoil. Increased surface roughness disturbs the flow of air around the airfoil causing early separation of flow. The separation decreases the lift and increases the drag of the airfoil. Ice accretion and surface roughness as low as number 40 sand paper can reduce the lift by 30 percent and increase the drag by 40 percent [4]. This also reduces the capability of autorotation of the rotorcrafts. In such a scenario, to maintain steady flight, we need to increase the rotor RPM which leads to increased power consumption. Higher power consumption in turn lead to increased fuel consumption and reduced operational envelope. The higher centrifugal forces cause the ice to shed off the rotor blades. Unsymmetrical shedding of blade ice leads to imbalanced aerodynamic loads and also induces vibrations in the structure. The occurrence of such events has led to fatal crashes of air vehicles [5].
To prevent such accidents and to alleviate the risks related to inflight icing conditions, anti-icing devices for critical parts like the icing boots for protection of the leading edge, heated pitot tubes, wind shield heaters and fuel vent heaters are developed and improved continuously. An ice protection system once developed needs to be certified by the FAA before getting the aircraft certified for Flight into Known Icing (FIKI) conditions. The main ways to perform the icing tests are to conduct tests in natural icing conditions and/or in flight artificial tests if the natural conditions do not provide all the test points necessary. During the development of the technologies, Wind tunnel tests are conducted [6]. Natural inflight tests have inherent threat of damage and loss of human and/or material property. Apart from that, significant amount of time and resources are spent in following the weather and the tests have very low repeatability due to constantly changing weather conditions. Artificial inflight test systems like HISS (Helicopter Icing Spray System)
have similar risks as natural inflight tests have. They also incur heavy operational costs and the repeatability is limited due to changing temperatures and winds. Wind tunnel testing on the other hand is risk free and has significantly lower operating costs. Test results have comparatively higher repeatability since the speed of air, Liquid Water Content (LWC), Total Water Content (TWC), temperature, and Median Volume Diameter (MVD) can be controlled. In some wind tunnels like the one locate at the Canadian Research Council (NRC) or Italian Aerospace Research Center (CIRA), altitude control is also possible [7]. Similarly, the aerodynamic characteristics of the wind tunnel like the turbulence intensity and angularity of the flow are constants for particular test section speeds. The ability to have control over all the above parameters can be of significant importance not only for research but also while testing of new components. Several wind tunnels of varying sizes with varying capabilities in terms of cooling capacity, test section velocities, droplet median volume diameter (MVD), duration to maintain the cold temperatures, purpose of testing etc. were developed since the 1930’s to investigate the issue of aircraft, sensors, and rotorcraft icing and to develop deicing and anti-icing methods.[1]

1.1 History and Development of Icing Research Tunnels over the last Century

During the late nineteen twenties, coordinated by the National Advisory Committee for Aeronautics (NACA) between various government agencies, research was to be conducted to find out the conditions of temperature and humidity, under which,
ice could form on the metal and fabric parts of the aircraft. It was hoped that once these conditions were known, instruments could be developed that could detect the conditions and warn the pilots of the impending dangers that befall them if continued along the given flight conditions. Also, it was expected to further research in development of anti-icing and deicing technologies. Inflight research was considered the most certain way to achieve results since the icing conditions were unknown as well as the means of duplicating the conditions within a wind tunnel were unavailable. A new icing wind tunnel was suggested to be built to conduct icing research, however, after certain considerations, the preliminary research was to be conducted in a 6 inch diameter test section of a refrigerated wind tunnel of NACA’s Langley Memorial Aeronautical Laboratory in Hampton, Virginia. The temperature inside the wind tunnel was to be controlled by brine solution which was cooled using commercial cooling system. Humidity was controlled by spraying water. Droplet size was controlled by controlling the water and air pressures in the spraying nozzles. Unfortunately the smallest droplet was still larger than what was found in natural icing conditions [1].

Before the wind tunnel tests had started, preparations for inflight investigation of icing conditions were underway under the supervision of NACA Chief Pilot Thomas Carroll. Research Authorization (RA) 247 gave research pilots Carroll and William H McAvoy the opportunity to investigate icing. With a modified Vought VE-7, equipped with an automatically recording air temperature thermometer and an automatically driven motion picture camera for providing visual observations, these two pilots commenced their flights in search of cloud formations where icing was
most likely to be encountered. It was learnt that Rime ice, usually took streamline shape, formed at lower temperatures, while glaze ice formed at temperatures just below 32 F (0 Degree Celsius), was clear looking and had rough leading edge[1].

Inflight tests also provided evidence that, compared to weight of ice, degradation of the airfoil properties caused by ice accretion on the leading edge had a more dominant effect. The above knowledge gave direction to the initial tests to be conducted in the wind tunnel. Several techniques to prevent ice buildup were suggested and tried in the wind tunnel. Six insoluble compounds, light and heavy lubricating oil, cup grease, paraffin and simonize wax were tested. Five soluble substances, glycerin, glycerin and calcium chloride, molasses and calcium chloride, a hardened sugar solution and a hardened glucose solution were also tested in the preliminary tests. None of the compounds helped to prevent ice accretion. It appeared that application of substances expedited the formation of ice. However, this led to one of the most important observation that the ice only accreted on the leading edge of the airfoil. A decision was made “Any preventive compound” should only be applied to the leading edge of the airfoil. This saved time and material / compound being tested on the airfoil [1].

A major breakthrough in anti-icing technology was achieved during April of 1930. Retired scientist William C Geer had started assessment of chemical methods for prevention of ice accretion in 1927. His research earned him the Daniel Guggenheim fund of $10,000 to conduct further research. Geer, a graduate of Cornell constructed a wind tunnel with 7 inch by 7 inch cross-section and 3 inch throat at Cornell, Department of Physics. It was here while working with B.F.
Goodrich that Geer came up with the “expanding rubber sheet” or “Ice-removing overshoe” which was conceptualized and made into a reality. The ice-removing overshoe is a rubber sheet installed on the leading edge of the wings, pressurized air used to inflate the rubber sheet to deice the leading edge. The rubber was coated with a mixture of pine, diethylene and castor oil in the ratio of 4:4:1. The tests to check the design were conducted towards the end of March under heavy icing conditions while flying between Cleveland and Buffalo [1]. As seen in Figure 2, an inflatable rubber sheet is installed on the leading edge of an airfoil. During normal operations, the rubber sheet is under suction and conforms to the shape of the airfoil. When accreted ice needs to be removed, pressurized air is sent to the boots and the ice breaks off the leading edge due to deformation of the leading edge and the ice is thrown away by the aerodynamics forces.
Goodrich developed then the largest Icing Research Tunnel (IRT) at Akron with overall dimensions of 10 feet X 40 feet with test chamber 3 feet X 7 feet X 6 feet. Cooling as low as –18° C. Liquid ammonia was used to achieve the required cooling using flood system. Goodrich Corporation later developed another bigger and better IRT in Uniontown Ohio and put it in operation in 1988 [1]. This wind
tunnel covered 40 feet X 70 feet and has cross sectional area 22 inch X 44 inch. Maximum wind speed reached was 103 m/s (200 knots). Humidity was introduced using the MOD-2 nozzles which were developed by NASA. This facility was more sophisticated compared to most other facilities. The turbulence intensity and flow angularity were quantified in this tunnel. The total cooling available is about 85 Ton [8]. A schematic of Uniontown, OH icing tunnel can be seen in Figure 3.

![Figure 3 Goodrich icing tunnel in Uniontown, OH](image)

After the development of icing boots and widespread installation on most of the aircraft, no research was conducted into icing. The icing issue was assumed to be solved and a problem of the past until the year 1937 when a TWA DC-2 flight crashed near Clifton, PA. The observers who reached the crash site noticed 1.5
inch of ice accreted on the leading edge of the ailerons. Icing had cost another thirteen lives [1]. After the accident, the NACA could no longer turn a blind eye towards icing and decided to build a new refrigerated wind tunnel to conduct research into deicing systems. The new wind tunnel actually had two underlying reasons to be built. One was to conduct icing research and the other was to carryout low turbulence variable density tests in search of new low drag airfoils. The cooling was obtained by using dry-ice to cool ethylene glycol which then cooled the tunnel. The tunnel could be cooled down to –6 degree Celsius (21.2 F) and could reach speeds of 36 m/s (70 knot). The minimum size of droplet was over 50 micron. Experiments performed here proved that engine exhaust has sufficient heat to deice the aircraft using heat alone. Once this was learnt, the wind tunnel tests for icing were cancelled and in-flight tests were conducted which brought in significant results. The tunnel was then dedicated towards the research of low drag airfoils [1].

What followed next was the birth of the most sophisticated facility for Icing Research, the present day NASA Glenn Icing Research Tunnel (IRT). The NACA in 1938 planned to build two new research facilities, one of them concentrating on engine research, Aircraft Engine Research Laboratory (AERL) in Cleveland, OH. This facility would simulate high altitude, low temperature conditions. The new icing wind tunnel that was to become the Icing Research Tunnel (IRT) was to be built adjunct to this facility and utilizing the excess available cooling. By design, aerodynamically this facility was not to be limited to icing tests, hence to save time, with certain modifications, the Moffett Field tunnel design was adopted [1].
In the final design specifications, the IRT covered an area of 200 feet X 75 feet. The test section has a cross section as 9 feet wide and 6 feet tall. The cross section is 25 feet long. The maximum air speed is 134 m/s (260 knot) and 180 m/s (350 knot) with a smaller section. The air is circulated by using an electric motor driven propeller. The cooling system is one of a kind and handles almost 7150 tons of Freon-12 helping the tunnel reach –29 degree Celsius (-20 F). The facility used spray nozzles similar to those used in the Goodrich facility. A modern spray-bar design was implemented. The nozzles were installed on a rotating airfoil 30 feet from the test section. During the calibration of the tunnel, it was impossible to get

Figure 4 Glenn IRT cross-section 6 feet X 9 feet [34]
a uniform cloud. The cloud uniformity tests were conducted by installing a mesh inside the cross-section that would accrete ice and thickness was measured. Changing the nozzles to those commercially available gave an even cloud however they could not produce small enough droplets. Nevertheless the tunnel was used to undertake research for better anti-icing equipment. By 1947, NACA had developed the required nozzles that produced droplets in required droplet size range from 5 to 200 micron. The nozzles were calibrated so that the MVD of droplets produced was a function of air and water pressures. During actual tests, the water pressure and air pressure close to the nozzle are monitored and MVD is predicted. The MVD was not measured in real time as done today. The water pressure is controlled based on the pressure of airline and the MVD requested. Several modifications have been done to the IRT to improve the efficiency of the tunnel in terms of working tunnel time, the appendix C conditions covered and replication of the inflight conditions. The drive motor was replaced in 1986. In 1999 the initially installed W shaped heat exchanger was replaced with a flat faced heat exchanger. New turning vanes were installed and dimensions were modified as well. All these changes have called for recalibration of the IRT time and again as they have a profound effect on the tunnel characteristics. Various extents of calibrations have been practiced from uniformity and LWC calibration only to tests including LWC, MVD distribution, turbulence intensity distribution, flow angularity distribution [9].
Boeing modified their existing aerodynamic wind tunnel to an icing wind tunnel and called it Boeing Research Aerodynamic/Icing Tunnel (BRAIT). The BRAIT featured three different cross-sections 5 feet X 8 feet with a maximum velocity of 77 m/s (150 knot). With using more constrictions, the area could be reduced to 4 feet X 6 feet with a velocity of 128 m/s (250 knot) and 3 feet X 5 feet with a velocity of 180 m/s (350 knot). BRAIT could operate in temperatures in the range – 40 degree Celsius to + 38 degree Celsius (-40 F to 100 F). The LWC ranges from 0.25 g/m$^3$ to 3.0 g/m$^3$. Hotwire anemometers quantified the turbulence intensity to 0.06 percent. The air is circulated around the tunnel with a 2000 HP fan drive system. The droplet size control is executed similar to NASA by controlling air and water pressure. The temperature control is exercised between ± 1 F [11].
The biggest facility for icing in the world is the Rail Tec Arsenal (RTA) in Vienna. It features a cross-section of 11.5 feet by 14.7 feet and length of 100 m (328 feet). The area can be contracted to almost half of the original size to 8.2 feet by 11.5 feet. The maximum velocity is 20 m/s in the original cross-section and reaches up to 80 m/s with the contraction. The droplet size range possible is between 15 and 40 micron. The tunnel can be cooled up to –30 degree Celsius (-22F). This facility is currently on-going icing cloud calibration efforts.
National Research Council Canada have an icing wind tunnel to carry out cold climate research related to aerospace, automotive, surface transport and marine industry. The tunnel has a square cross-section of 22.5 inch by 22.5 inch and a length of 70 inch. The maximum speed is 100 m/s (195 knot) and can achieve up to 180 m/s (350 knot) by reducing the cross-section. The tunnel can reach as low as -40 degree Celsius (-40 F) and the turbulence intensity recorded is 0.9 percent. LWC can be controlled between 0.1 g/m$^3$ to 3.5 g/m$^3$. This tunnel can simulate different altitudes from ground level up to 40,000 feet [12][7]. A schematic of NRC Altitude Wind Tunnel is shown in Figure 8.

Apart from the above mentioned icing Wind Tunnels, there exist multiple professional and research icing tunnels with different capabilities. Universities like Iowa State, Cranfield or the German Aerospace Center (DLR), Italian Center for Aerospace Research have icing wind tunnels conducting research as well.
Penn State Icing Wind Tunnel is a newly constructed vertical closed circuit and partially enclosed in a freezer icing tunnel. The tunnel has two different cross sections, a vertical cross-section that is 20 inch X 20 inch and a horizontal cross-section 36.5 inch X 24.5 inch. The maximum velocity in the vertical cross-section is 77 m/s (150 knot) at – 30 degree Celsius (-22 F) and in the horizontal cross-section 36 m/s (70 knot). There is a single spray bar located on top of the vertical cross-section and consists of four NASA standard nozzles. The facility can produce supercooled and mixed phase icing clouds. The horizontal cross-section can be used for engine icing tests while the vertical cross-section can be used for testing of pitot tubes [5]. The flow quality and cloud in the vertical test section have not been quantified.
1.2 Thesis Objectives

The objective of this thesis is to characterize the vertical test section of the Penn State Icing Tunnel (PSIT) following the guidelines provided in SAE Aerospace Recommended Practices (ARP 5905): Calibration and Acceptance of Icing Wind Tunnels. To achieve the thesis goal, following objectives were laid down.

1. Iterate the nozzle positions to obtain a uniform icing cloud in the cross-section.
2. Calibrate a hot wire anemometer to quantify the centerline turbulence intensity, turbulence intensity distribution, centerline velocity and velocity distribution in the cross-section.
3. Calibrate differential pressure transducers to quantify the flow angularity in the cross-section using a five holes three dimensional flow angularity probe.

4. Quantify the LWC in the test section by changing the nozzle parameters as well as number of nozzles.

5. Quantify Median Volume Diameter (MVD)

1.3 Thesis Overview

1.3.1 Chapter 2: Liquid Water Content Theory
The mathematical approach to quantify LWC is reviewed. MATLAB code to measure LWC from experimental data is presented along with modifications to the existing code to increase the LWC calculation speed.

1.3.2 Chapter 3: Cloud Uniformity, LWC calibration and MVD calibration
Experimental work to achieve cloud uniformity is presented. The LWC and droplet MVD distribution is discussed.

1.3.3 Chapter 4: Aerodynamic calibration
Experimental work quantifying turbulence intensity and flow angularity is presented.

1.3.4 Chapter 5: Conclusions and Recommendations
Conclusions are drawn from the presented results. Recommendations for future work to improve the capability and coverage of the Appendix C, 14 FAR Part 25 icing envelope are mentioned.
Chapter 2

2. Liquid Water Content Theory

Liquid water content is the amount of water present in the clouds and is measured in grams per cubic meter. Higher LWC results in faster accretion of ice on the airfoil. It is one of the most important parameter used to define icing envelopes specified in 14 FAR part 25 Appendix C and Appendix O. Next sections review the equations used in energy analysis and to calculate the LWC.

2.1 Cloud Uniformity and Liquid Water Content Calibration

The liquid water content is calculated by

\[ LWC = \frac{K_1 \cdot \rho_{ice} \cdot \Delta_s}{E_b \cdot V \cdot \tau} \]  (1)

Where \( K_1 \) is a constant and depends on the units of other parameters, \( \rho_{ice} \) is the density of ice in kg/m\(^3\), \( \Delta_s \) is the thickness of ice accreted in inches, \( E_b \) (\( \beta \)) is the collection efficiency is dimensionless, \( V \) is the velocity in the test section in m/s and \( \tau \) is the time of exposure of the mesh / body to the icing cloud in seconds [14].

To calculate the LWC, the thickness is measured at the stagnation point of the airfoil / cylinder hence the collection efficiency to be calculated is the stagnation collection efficiency. It is given by [15]

\[ \beta_0 = \frac{1.4 + (K_0 - \frac{1}{2})^{0.84}}{1 + 1.4 + (K_0 - \frac{1}{2})^{0.84}} \]  (2)

Where \( K_0 \) is the modified inertial parameter given by
\[ K_0 = \frac{1}{8} + \frac{\lambda}{\lambda_{stokes}} \left( K - \frac{1}{8} \right) \]  

(3)

\( K \) is the inertia parameter and \( \frac{\lambda}{\lambda_{stokes}} \) is the droplet range parameter [15].

The droplet range parameter is defined as the ratio of actual droplet range to droplet range if stokes drag law for solid spheres is applied. It is the function of droplet Reynolds number and given by following equation [15].

\[ \frac{\lambda}{\lambda_{stokes}} = \frac{1}{0.8388 + 0.001483 \times Re_\delta + 0.1847 \times \sqrt{Re_\delta}} \]  

(4)

And the droplet Reynolds number is given by [15]

\[ Re_\delta = \frac{V \times \delta \times \rho_w}{\mu} \]  

(5)

The inertia parameter is given by [15].

\[ K = \frac{\rho_w \times \delta^2 \times V}{18 \times d \times \mu} \]  

(6)

\( \delta \) is the MVD of the droplets, \( \mu \) is the viscosity of air.

The collection efficiency is one of the most important parameters that need to be calculated precisely to ensure accurate measurement of LWC. The collection efficiency is analyzed using either Lagrangian or Eulerian approaches. A new approach of calculate the collection efficiency is reviewed by Da Silveira [16]. There is no particular advantage of using Lagrangian method over Eulerian approach. Both have been proven to yield equally accurate results. The Lagrangian approach is computationally cost effective as it simulates icing only on specific strips. The Eulerian approach is computationally heavy as it involves
solving for the flow field simultaneously with mass and momentum conservation equations. The Lagrangian approach requires the flow field to be steady which is not condition for Eulerian approach and hence for applications involving rotorcraft, Eulerian approach is more suitable [17]

2.2 Icing Regimes

Aircraft icing can be divided into two basic regimes, rime ice and glaze ice. A third type of ice, a combination of both rime and glaze can form as well. Rime ice is characterized by its milky and opaque appearance. It generally forms at lower LWC, smaller droplets and lower temperatures (generally below -15 degree Celsius (5 F)). It freezes immediately on impact and hence takes an aerodynamic shape. It is generally easy to remove. Glaze ice on the other hand is clear and forms just below freezing temperatures (2 to -10 degree Celsius (34 F to 14 F)). It is formed in higher LWC conditions compared to rime ice and has a particular characteristic of having horns as the water may not freeze instantaneously on impact. It is harder to remove as compared to rime ice and is the most dangerous form of icing. Mixed ice is formed between – 10 to – 15 degree Celsius (14F to 5F) [18].
The type of cloud can suggest the intensity of icing that can be expected to be encountered. Stratus clouds exist usually below 15,000 feet and their icing layer thickness usually extends for 3000 feet. They usually contain low amount of liquid water and the temperatures are pretty low and up to −45 degree Celsius and may extend for hundreds of miles. The cumulus clouds can be found up to 30,000 feet. They have significantly higher liquid water content and extend only up to 2 to 7 miles horizontally. The temperatures exist between +2 to −20 degree Celsius, and it also contains bigger droplet sizes [17].

2.3 Appendix C and Appendix O

A brief review of 14 FAR part 25 Appendix C and Appendix O is valuable to compare the cloud conditions that can be sprayed in the wind tunnel and to make appropriate efforts to increase the conditions that can be covered. It gives the ranges of LWC, MVD, Temperatures and pressures against which the ice protection system needs to be designed. As PSIT is not an altitude icing wind tunnel, all tests are run at normal atmospheric pressure. As the altitude increases, the pressure decreases. A study of effect of drop in pressure on ice accretion was
performed at CIRA wind tunnel in Italy. The results concluded with small changes observed near the leading edge of the airfoil while the droplets reached further back along the chord as pressure decreased (altitude increased) [20].

2.3.1 Appendix C
Appendix C of 14 FAR part 25 has been in use since the mid-sixties which facilitate selection of cloud parameters in design of ice protection systems. It is divided into two parts, continuous icing conditions in the Stratiform or layer type clouds and intermittent icing conditions experienced in cumuliform clouds. Continuous icing conditions have traditionally been applied to airframe ice protection systems and intermittent icing conditions are used in the design of engine ice protection system [3].

The continuous conditions extend from sea level to an altitude of 22,000 feet and the horizontal extent from 5 miles to 310 miles. Depending upon horizontal extent of the clouds, a liquid water content factor is introduced which multiplies with the nominal liquid water content to give the total liquid water content to be expected and the system to be designed for. The maximum LWC including the factor for continuous conditions is 1.072 g/m³. The ambient temperatures to be tested extend from 0 to -30 degree Celsius (32 F to –22 F). The MVD sizes are expected to be between 15 and 40 micron [3]. Figure 11, Figure 12 and Figure 13 define the appendix C for continuous icing conditions.
Figure 11 Temperature and altitude extent for continuous icing envelope of Appendix C [3]
Figure 12 LWC and MVD extent for continuous icing envelope of Appendix C [3]
For the intermittent maximum, the maximum LWC including a maximum liquid water content factor of 1.35, is 4.05 g/m$^3$. The horizontal coverage of the cloud is between 0.3 mile and 6 mile. The vertical extent is from 4000 to about 29,000 feet. The lowest temperature is – 40 F and the biggest particle size is 50 micron [3].

*Figure 13 LWC factor based on distance [3]*
Figure 14 Temperature and altitude extent for intermittent icing envelope of Appendix C [3]
Figure 15 LWC and MVD for intermittent icing envelope of Appendix C [3]

Figure 14, Figure 15 and Figure 16 define the appendix C intermittent conditions.
2.3.2 Appendix O

The Roselawn crash of 1994 involving an ATR – 72 initiated interest in droplet sizes larger than that in appendix C conditions [21]. A new Appendix O was created to certify aircrafts for Supercooled Large Droplets (SLD) icing conditions. Appendix O consists of freezing drizzle and freezing rain categories. Both the freezing drizzle and rain have been defined for clouds with MVD less than 40 micron and greater than 40 micron. Such conditions are usually noticed under stratiform clouds [22].
The Freezing drizzle has been defined from 0 degree Celsius (32 F) to –25 degree Celsius with maximum LWC at 0 degree Celsius of 0.44 g/m$^3$. With the maximum LWC factor of 1.266, the maximum LWC for appendix O in freezing drizzle is 0.55 g/m$^3$. Freezing drizzle is expected between Sea Level and an altitude of 22,000 feet.

Figure 17 LWC and ambient temperature extent for freezing drizzle conditions of Appendix O [22]
Figure 18 MVD distribution for freezing drizzle [22]

Figure 17, Figure 18 and Figure 19 define the freezing drizzle conditions for Appendix O.
Compared to freezing drizzle, freezing rain has a higher temperature limit of \(-13\) degree Celsius and a maximum LWC of \(0.4 \text{ g/m}^3\), and altitude limit of 12,000 feet.

Figure 20, Figure 21 and Figure 22 define the freezing rain for Appendix O.

Figure 23 indicates the liquid water content factor for appendix O. The equation for the line is given by

\[
S = 1.266 - 0.213 \times \log_{10} H
\]  

\(S = \text{LWC factor and } H = \text{Horizontal extent in nautical miles.}\)
Figure 20 LWC and temperature extent of Appendix O in freezing rain [22]
Figure 21 MVD distribution in freezing rain condition for Appendix O [22]
Figure 22 Temperature and altitude extent for freezing rain [22]
2.4 LWC Calculation

The LWC in the cross-section is assessed by measuring the thickness of ice accreted on a mesh. The energy balance analysis at the stagnation point is briefly discussed next.

The thickness of ice accreted is given by the equation

\[ \Delta = n_a \times A_c \times \beta_0 \times d \]  \hspace{1cm} (8)

Where \( n_a \) is the freezing fraction and defined as the fraction of water flux entering a control volume that freezes within the control volume. Its value ranges from 0 to 1 [15].
\( A_c \) is the accumulation parameter and has the formula

\[
A_c = \frac{LWC \cdot V \cdot \tau}{d \cdot \rho_i}
\]  

(9)

The collection efficiency is given by \( \beta_0 \) and \( d \) is the cylinder diameter or twice the leading edge radius of an airfoil.

The analytical freezing fraction can be defined as

\[
n_a = \frac{C_{p,ws}}{A_f} \cdot (\phi + \frac{\theta}{b})
\]  

(10)

\( \phi \) is the water energy transfer parameter

\( \theta \) is the air energy transfer parameter and

\( b \) is the relative heat factor

\[
\theta = (t_s - t_{st} - \frac{r \cdot V^2}{2 \cdot C_p}) + \frac{h_G}{h_c} \left( \frac{P_{ww}}{T_{st}} \frac{P_{tot}}{T_{tot}} \frac{P_{w}}{T_{tot}} \frac{P_{ww}}{T_{st}} \right) \Lambda_V
\]  

(11)

\[
\phi = t_f - t_{st} - \frac{V^2}{2 \cdot C_{p,ws}}
\]  

(12)

\[
b = \frac{LWC \cdot V \cdot \beta_0 \cdot C_{p,ws}}{h_c}
\]  

(13)

\( h_G \) is gas phase mass transfer coefficient given by

\[
h_G = \frac{h_c}{C_p} \left( \frac{Pr}{Sc} \right)^{0.67}
\]  

(14)

\( Pr \) is the Prandtl number and \( Sc \) is Schmidt number given by

\[
Pr = \frac{C_{p,\mu}}{k_a}
\]  

(15)
\[ Sc = \frac{\mu}{\rho*D_v} \]  \hspace{1cm} (16)

respectively.

\[ h_c = \frac{k_o}{d} * Nu \]  \hspace{1cm} (17)

hc is the convective heat transfer coefficient.

The Nusselt number is calculated differently at different Reynolds numbers [15]

\[ Nu = 1.14 * Pr^{0.4} * Re^{0.5} \]  \hspace{1cm} (18)

\[ Nu = 1.1 * Re^{0.472} \]  \hspace{1cm} (19)

\[ Re = \frac{V*d*\rho}{\mu} \]  \hspace{1cm} (20)

The MATALB code developed by former member of the laboratory, Yiqiang Han [23], first calculates the freezing fraction analytically, as shown above and then equates it to the experimental freezing fraction. There are four different empirically developed relations that corelate the analytical freezing fraction to experimental freezing fraction. An appropriate correlation is selected based on ice shape research conducted previously. Once the experimental freezing fraction is known, the ice thickness is calculated analytically using equation 8.

Once the values of accretion parameter, collection efficiency, diameter and freezing fraction are input, the only variable is the LWC. As the LWC value increases, the calculated thickness increases. Using this logic, the analytically calculated experimental thickness is equated to measured thickness. The range of LWC values for which the two thicknesses match is the LWC sprayed in the cross-section.
A .DAT file provides the input to the MATLAB code. The inputs include the chord length of the airfoil or diameter of the cylinder, static temperature in the test section, velocity in the test section, the MVD of the test, the duration of the test and the thickness of ice accreted on the airfoil / cylinder.

From the above data of temperature and velocity, the film temperature, Mach number, static pressure, Reynolds number are calculated. The chord defined is used to calculate the Reynolds number, inertia parameter and accumulation parameter. Time is used to calculate the accumulation parameter which is used to calculate the thickness. Other constants like density of water, ice, latent heat of evaporation and freezing are defined along with temperature dependent parameters like viscosity (µ), vapor pressures, specific heat of water [15].

2.4.1 Modification to the Code

Instead of using an iterative approach, the code was redesigned to solve for LWC using a Newton Raphson method. After substituting the values of accretion parameter, collection efficiency, diameter and freezing fraction, a linear equation with LWC as the only variable is obtained.

2.4.1.1 Newton Raphson Method

Newton Raphson method or Newton’s method is used to find the roots of a function. The root(s) of a function can be found if the function is continuous and differentiable near the roots. An initial approximate guess of the solution needs to be provided to solve the equation / function.
Let \( f(x) \) be a continuous differentiable function and let \( f'(x) \) be the first differential of the function. Let \( x_1 \) be an initial guess solution and \( x_2 \) be the more refined solution. \( X_2 \) then is given by the following equation.

\[
X_2 = X_1 - \frac{f(X_1)}{f'(X_1)}
\]

The above process is carried out until the successive solutions converge. Convergence is usually achieved when successive solutions have five digits post decimal point common, however in the current context, the level of accuracy desired is not that high.

The above method provides a faster solution and accurate values. Another way that is also being implemented is to use an inbuilt solver of MATLAB, solve. As the equation obtained has is linear in LWC, solve function evaluates the value and can give an accurate output.
Chapter 3

3. Cloud Uniformity and LWC Calibration

3.1 Cloud Uniformity and Liquid Water Content Calibration

Icing wind tunnels are large scale instruments that can be used to test or redesign ice protection systems (IPS). Just like any other instrument, the icing wind tunnels should be calibrated to guarantee accuracy and repeatability of tests. The Society of Automotive Engineers (SAE) Aerospace Recommended Practices (ARP) 5905 provides practices for calibration of icing tunnels that are used to test aircraft components in icing environments. The ARP however is not applicable to air breathing propulsion test facilities. The standards describe different extents of calibrations and frequency of calibration [24].

A baseline calibration is a complete calibration performed during commissioning of the tunnel as well as after a major facility modification (change of evaporator, tunnel area modifications etc.) that may result in change in icing cloud distribution. If no modifications are performed, it is recommended to perform a baseline calibration once every five years.

Interim calibrations are performed on an annual basis for first two years following a commissioning calibration or a major facility modification. As a minimum, the interim calibration compares the cloud uniformity and axial centerline LWC with the established baseline results. If the interim calibration shows a shift in the
performance, fixes should be attempted, however if the calibration is out of sync and results indicate shift in values compared to the previous calibration, a baseline calibration should be performed. The MVD calibration is also included in the interim calibration.

Lastly there is check calibration that is performed every six months unless it is succeeded by a baseline and interim calibration. It involves cloud uniformity check and centerline LWC measurements and similar to interim calibration, if there are significant differences from the established baseline calibration, the issues need to be cleared and if they persist, a new baseline needs to be established after performing desired modifications. Ice shape continuity check can be performed after completion of each of the calibration efforts. It involves accreting ice on a particular model. For shape continuity, the cloud conditions and the model used for accretion should be the same every time [24].

Cloud uniformity in the cross section implies having supercooled liquid water distributed evenly throughout the cross-section i.e. from wall to wall. The aim is to iterate for nozzle positions to get as wide of an icing cloud as possible. However the size of the uniform cloud is limited and does not actually spread from wall to wall due to several reasons including but not limited to boundary layer formations, flow characteristics of the tunnel, flow over spraybars etc. [21]. The ARP has defined a uniform cloud that has a variation in thickness of ice accreted of ± 20 percent of the tunnel centerline thickness [24].
NASA Glenn has been calibrating the IRT and most of the other icing tunnel operators have followed NASA Glenn’s footsteps. NASA accretes ice on vertical pipes (now a square mesh). The thickness of ice accreted is recorded either manually by using a chilled micrometer or digital calipers or by using an automated system developed by NASA in 1993. Chilled micrometers were used in the early calibration efforts of the IRT. A new instrument developed in the nineties, measured ice thickness using LVDT. The instrument was mounted on a traverse. A microstepping indexer and motor were used to control the motion of the system. The system had a resolution of ± 0.015mm to measure ice thickness and the traverse could be positioned within ± 5.65 mm. This system reduced the time spent on measurement by half and took an hour to get all the thickness measurements. The system recorded thickness continuously instead of recording discrete points and plotted the uniformity graphs in a matter of minutes after completion of tests [25]. The 2012 wind tunnel calibration reports of NASA states the ice thickness measurements done manually using digital calipers [26]. This may be due to change in the ice accreting mesh used. In the earlier calibration efforts, 2 inch diameter pipes installed at nine different positions were used which changed to a mesh 2 inch deep with a flat 1/8 inch which has spacing of 6 inch X 6 inch and is 6 feet X 6 feet, installed in the center of the tunnel cross-section.
A direct spatial relation between the nozzle position and cloud distribution in the test section is absent, therefore several tests need to be run to determine the spray area and location of the individual nozzles. The absence of spatial relationship can be attributed to nonuniform airflow over spraybars and tunnel contractions. Once the spray locations for individual nozzles and their orientation is known, the process of adding and removing active nozzles (nozzles that spray the cloud) can be streamlined and a uniform icing cloud now can be iterated. The cloud uniformity in all the tunnels takes up the maximum time and effort of the calibration efforts. It involves significant trial and error to get a uniform cloud [9].
Once the cloud uniformity is achieved, a standard icing blade is used to measure
the LWC at the center of the test section. The tunnel is brought up to the required
speed and is allowed to stabilize in terms of speed and temperature. Once the flow
has stabilized, the spray nozzles are turned on and ice is allowed to accrete on the
icing blades. The droplet size is controlled by controlling the air and water
pressures. The through method of control of MVD will be covered in detail in the
next section. The liquid water content of the cloud is a function of the median
volume diameter of the droplets, the velocity of the tunnel, the airline pressure in
the nozzles and whether the nozzles are Standard or MOD-I. Once the ice is
accreted, the thickness is measured by the procedure mentioned above and LWC
is measured using the FWG two-dimensional droplet trajectory code which uses a
Hess-Smith panel code for flow field prediction and a C. W. Gear Stiff equation
scheme to integrate particle trajectories [14].

A baseline calibration was performed for the Penn State Icing Tunnel (PSIT). The
tunnel has a single spray bar with four NASA standard nozzles and no MOD-I
nozzles. The nozzles differ in terms of their water exit orifice diameter, which
affects the LWC of the cloud. The diameter of the standard nozzles is 0.635 mm
(0.025 inch) and the nozzle diameter of the MOD-I nozzles is 0.3937 mm (0.0155
inch). For the same differential pressure between air and water lines at a constant
airline pressure the MOD-I nozzles create smaller MVD droplets compared to the
standard nozzles and hence have a lower LWC [14]. Each nozzle has a separate
air and water supply and the pressures are checked at the main manifold before
the supply bifurcates to feed individual nozzles. A feedback ensures the pressure
at the manifold is the one requested by the operator to control the air pressure and the MVD of the particles.

The spraybar assembly is made up of an aluminum cylinder with a diameter of 12 inch and height of approximately 30 inch. The nozzles are mounted inside the cylinder using L brackets and goosenecks to easily change the orientation of the nozzles. Resistive heaters are installed on the inner circumference of the cylinder to prevent freezing of the waterlines by heating the air around the waterlines. The cylinder is mounted at the top of the vertical test section. The cylinder with the heaters and without the goosenecks can be seen in Figure 26.

Figure 25 Spray system schematic in PSIT
A square steel mesh with cylindrical rods of diameter of 0.078 inch spaced one inch apart covering the whole cross-section of 20 inch X 20 inch is used to accrete ice. Once ice has been accreted, the mesh is transferred to the freezer to measure the ice thickness using a chilled caliper. The thickness variation is used to determine cloud uniformity and thickness values to measure LWC in the cloud.
Ice is allowed to accrete on the mesh for 45 seconds for all the LWC tests. A longer exposure to the cloud changes the collection efficiency, impacting the shape of accreted ice and hence the heat transfer rates. The heat transfer rates govern the growth of ice shapes and thickness. The thickness of ice accreted per unit time and the collection efficiency are used to calculate the LWC in the cross-section. The forty-five second time limit satisfied the minimum thirty second limit to establish temporal uniformity and also allowed for accretion of measurable thickness [24].
The tests for cloud uniformity took place in the month of March 2017. Initial tests were conducted with the mesh positioned at the very end of the test section as shown in Figure 28. Individual nozzles were sprayed by cutting off water and air supply to the remaining nozzles. It was learnt that the cloud concentrated only at certain area for all the nozzles as shown in Figure 29. The orientation of nozzles or that of the spray bar did not affect this cloud distribution. On realizing that the location of the mesh is too close to the turning vanes and that no tests will be conducted so close to the turning vanes, a decision was taken to measure the cloud uniformity about 9 inches above the turning vanes as indicated in Figure 30. This was achieved by making a stand to which the mesh was attached using zip ties. The mesh can be seen installed on a 9 inch long stand in Figure 31. It was speculated that the aerodynamic effect of the turning vanes forced the cloud
to accrete at a particular position. The speculation was asserted to be true when the cloud was evaluated using the stand as the accretion area and cloud uniformity changed for different velocities and different orientation of nozzles and spray bar.
In the final configuration, all the four nozzles were used to obtain a uniform cloud. The center area of the mesh of about 11 in X 11 in has a uniform cloud. Since the LWC is linearly proportional to the ice thickness, an ice thickness measurement within ±20 percent of the thickness at the center of the tunnel determined a uniform cloud.

*Figure 30 Mesh on a 9" stand in the cross-section*
It was learnt from IRT calibrations and experiments that as the tunnel velocity increases, the uniformity decreases [21]. The uniformity tests in the PSIT were conducted at 50 m/s. It was expected that for lower speeds, the uniformity would be maintained if not improved. The reduction in uniform area is seen in Figure 33 as the velocity changes from 0 m/s to 15 m/s and in Figure 34 as speed changes from 30 m/s to 50 m/s. Uniformity tests laid the foundation to test droplet distribution, velocity uniformity, turbulence intensity distribution and flow angularity distribution.
The aim in the vertical test section is to have supercooled liquid water to test Appendix C icing test conditions. That means droplet particle sizes up to 50 micron maximum are required and they should be only supercooled and not fully glaciated ice crystals. Once a droplet exits the high pressure of the nozzles, the pressure differential supercools the droplets. If the pressure difference is too high, the droplets freeze out. If a mixed phase cloud exists, i.e. supercooled water and fully glaciated ice crystals co-existing, the liquid water accretes on the object of interest and the ice particles erode the accreted ice. Thus, resulting in incorrect ice shapes and ice thicknesses and hence incorrect LWC measurement. For this reason, the air pressure condition that provided such multi-phase cloud was experimentally identified.

Figure 32 Graph of distribution of cloud in the cross-section
While quantifying the LWC in the tunnel, the first step was to determine at what airline pressure ice crystals are created along with super cooled water droplets. Tests were run for similar conditions of temperature, velocity and droplet size. The airline pressure was varied from 35 psig to 15 psig. The maximum accreted ice on the mesh was at 20 psig airline pressure. Similar trials were conducted at a
comparatively warmer temperature of -10 degree Celsius and same results were obtained. It was concluded that freeze out occurs at airline pressures above 20 psig. The rationale for such conclusion is that as the airline pressure increases, so does the difference in pressure between water and air lines, and therefore the flow rate to the nozzle increases. As the airline pressure increases, it is expected a higher LWC correlating to higher ice thickness. The fact that the ice thickness decreases with increasing airline indicates the existence of glaciated droplets that do not accrete. For supercooled droplets, the airline pressures were limited to 15 and 20 psig. Pressures below 10 psig are too low for the nozzle software to accurately control pressure and hence cannot be used. Since the pressure is increased by 5 psi in every step, airline pressures were limited to 15 and 20 psig.

\[ LWC = k \left( f(P_{air}, V) \times \frac{\sqrt{\Delta P}}{V} \right) \]  

The LWC that can be sprayed are as follows,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 g/m³</th>
<th>2 g/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVD (micron)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Temperature (degree Celsius)</td>
<td>-15</td>
<td>-15</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Airline Pressures (psig)</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>
3.1.1 Verification of results using LWEINT

As the LWC is now calibrated in the tunnel, this exercise was conducted to compare the ice thicknesses from LEWICE / LEWINT to those measured from the tunnel during the calibration. It serves the purpose of self-verification. LEWINT is a software developed by a private company and runs LEWICE in the background, a code developed by NASA Glenn Research Center (GRC) to predict ice shapes on an airfoil or other geometries, design anti icing or IPS and further to measure performance degradation on airfoils not only in CFD but also experimentally [28].

Two versions of LEWICE based on the geometry, a two dimensional and a three dimensional version are available to carry out the prediction. A two dimensional version is used in this study. The code takes as input the geometric shape, chord, atmospheric conditions like the temperature, LWC, droplet distribution, relative humidity, atmospheric pressures etc. along with the velocity and duration of exposure to the cloud. The code then runs to predict ice shapes by calculating the collection efficiency and performing the heat transfer analysis on the geometry. The ice shapes developed by the code have been validated against variety of atmospheric conditions and varying geometries [28].

A single body was defined and input to LEWINT. The geometry is defined in a text file. Each line in the text file contains x and y coordinates for the geometry. The geometry is normalized by chord. One of the cylinder of the mesh is defined in the geometry. A standard geometry file has anywhere between 50 to 150 rows defining the geometry. The file used in the analysis contained 361 points. The co-ordinates begin at leading edge and move anti clockwise to complete a circle. However
LEWICE can detect if the data points are input clockwise and can correct points for input [28].

Tests were run at 1 g/m$^3$ and 2 g/m$^3$ for 50 m/s and 40 m/s respectively. Temperature was set to 258.15 k. Atmospheric pressure used is 101,325 Pa. Initial experiments were run at 2 g/m$^3$. The stop time (TSTOP) was set for 45 seconds. The tests failed to yield an ice shape. The junk. DAT file output reading “Strange things may have happened to ice shape!” and suggested using larger value of DSMN. DSMN defines the minimum size of the control volume and is a non dimensionalized term. Larger value of DSMN lowers the number of control volumes and uses fewer panels. The standard DSMN values range between 0.0002 and 0.0008. The manual for LEWICE does not specify a DSMN value for cylinders and also specified no data had been experimentally verified for cylinders.

A study was performed keeping all the parameters but DSMN constant. The tests are run to determine the effects of DSMN on ice shapes. An ice shape was obtained at DSMN value of 0.0008. For higher values of DSMN, incomplete ice shapes were obtained. Hence it was decided to use DSMN value of 0.0008.

In terms of normalized thickness, the ice accreted on the mesh was over 2. There is a limitation on maximum ice accreted in a time period and for higher LWC’s the thickness accreted was not accurately predicted. The ice thickness predicted was lower by 25 percent.

To counter the issue, two alternatives were tests. First, as the thickness is linearly proportional to the duration of accretion. It was decided to use lower time limits to
predict the thickness and linearly extrapolate the thickness to duration of tests. The second alternative was to run a shorter duration test and rerunning the output file as the input file with the accreted ice as a part of the input geometry.

Both the methods were tested. As the time of ice accretion was 45 seconds, the smaller times used were 15 sec, 9 sec and 5 sec. Ice was accreted for all the cases and multiplied by appropriate factor.

*Table 1 Normalized ice thickness predicted by multiplying by a factor for 2 g/m³*

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>MULTIPLICATION FACTOR</th>
<th>NORMALIZED THICKNESS</th>
<th>EXPERIMENTAL NORMALIZED THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>1.812</td>
<td>2.19</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>1.84</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>1.855</td>
<td></td>
</tr>
</tbody>
</table>

The ice thickness was then predicted for shorter durations and then iterated for until the test of duration. For an LWC of approximately 2 g/m³. The under prediction is reduced to 15.3 percent from 22.83 percent.
Table 2 Normalized ice thickness predicted by additional repetitions for 2 g/m³

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>ADDITIONAL REPETITIONS</th>
<th>NORMALIZED THICKNESS</th>
<th>EXPERIMENTAL NORMALIZED THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>0</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>1.822</td>
<td>2.19</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>1.84</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>1.855</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 indicates the duration of a test in column 1 and column 2 (repetition) indicates the number of additional repetitions performed on the output of previous step to get the normalized thickness as mentioned in column 3 (Normalized Thickness). We can see that both methods give out similar results and better predict the thicknesses on the cylinder. The ice shaped predicted in Figure 35 indicate the improvement over running one test for full test duration.
A similar study was performed for $1 \text{ g/m}^3$ LWC and the results are as below.

**Table 3 Normalized Thickness predicted for 1 g/m³**

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>MULTIPLICATION FACTOR</th>
<th>NORMALIZED THICKNESS</th>
<th>EXPERIMENTAL NORMALIZED THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>1.152</td>
<td>1.41</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>1.16</td>
<td></td>
</tr>
</tbody>
</table>
The under prediction for 1 g/m³ reduced from 21 percent to 17 percent.

The higher under prediction obtained when running a case for the complete duration of the test may be explained by the fact that the diameter of the cylinder used in the experiment is about 180 times shorter than the data LEWICE has been validated for. As the thickness accreted is a function of chord and high amount of ice accreted on cylinder may cause the collection efficiency to be calculated incorrectly. From the data observed above, it can be concluded that for small cylinders, to match the stagnation ice thickness, we can run higher repetitions of predicted ice shapes or use smaller durations and multiple by appropriate factor to yield correct thickness.

### 3.2 Median Volume Diameter

The median volume diameter is used to characterize the droplet size distribution in a cloud. Median Volume Diameter, also known as Mean Effective Diameter, is defined as the droplet diameter where half of the water in a cloud by volume is contained by the droplets with diameter smaller (or larger) than this diameter [21].

MVD for a test is maintained constant by maintaining the air and water pressures, a series of tests conducted at Icing Research Tunnel, NASA Glenn Research Center, by varying the air pressures and water pressures successively helped study the MVD generated by the nozzles. Based on the air pressure and the water pressure, the MVD of droplet particles was measured in the tunnel. Two optical
instruments, for measuring droplet sizes, for different ranges of droplet sizes are used. The FSSP (Forward Scattering Spectrometer Probe) was used to quantify the particle sizes between 5 and 50 micron. The Optical Array Probe (OAP) was used to measure the sizes between 47 micron and 457.5 micron. From a sample volume, these instruments segregated the droplet sizes into various size bins. Once this distribution is known, the MVD was calculated by the instruments. For detailed working of the instruments, the reader is directed to [29] from the references. The process is repeated for MOD – I nozzles. The water pressure is made a function of air pressure and MVD. A curve fit was performed using the least squares method for the collected data using a commercially available software tool with parameters $P_{\text{air}}$ and $\Delta P$ to find the equation that fit as closely as possible. The equation has the form as given below.

$$MVD = \exp(a + bx + cy + dx^2 + ey^2 + fyx + gx^3 + hy^3 + iy^2x + jyx^2)$$

Where $x$ is the natural log of the gauge air pressure in psi and $y$ is $\Delta P$ in psi and the coefficients for MOD – I and Standard nozzles are mentioned in the table below [21].

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>MOD 1 Nozzles</th>
<th>Standard Nozzles</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>8.748044966</td>
<td>15.86986874</td>
</tr>
<tr>
<td>b</td>
<td>-5.758889866</td>
<td>-13.19240311</td>
</tr>
<tr>
<td>c</td>
<td>0.138821237</td>
<td>0.972293768</td>
</tr>
<tr>
<td>d</td>
<td>1.698096143</td>
<td>4.129785202</td>
</tr>
<tr>
<td>e</td>
<td>4.861 92E-05</td>
<td>0.001586357</td>
</tr>
<tr>
<td>f</td>
<td>-0.067544202</td>
<td>-0.49291007</td>
</tr>
<tr>
<td>g</td>
<td>-0.165992209</td>
<td>-0.416788168</td>
</tr>
<tr>
<td>h</td>
<td>8.85362E-08</td>
<td>1.70613E-07</td>
</tr>
</tbody>
</table>
Once the MVD and airline pressure is fixed, differential pressure is calculated and water is pressurized to the required pressure. As the airline pressure is increased the water pressure required to maintain the MVD increases and so does the differential pressure between airline and waterline. The LWC is directly proportional to square root of differential pressure, hence as the airline pressure increases, the LWC increases [14]. As a result, we would expect a higher thickness accreted on the mesh. However due to a high differential pressure between the nozzle and the test section, certain droplets freeze completely. This is known as droplet freeze out and frozen droplets are called ice crystals. Ice crystals do not accrete on the mesh and they erode the accreted ice. Thus measuring a lower thickness on the mesh.
Figure 36 Droplet size calibration curves for Standard nozzles

Commercially available droplet sizing instrument was rented to calibrate the MVD in the PSIT. Microtrac from Aerotrac is an optical instrument, shown in the Figure 38. The unit can rate various types of particles (powder / oils / water) by the principle of laser diffraction in the range of 0.5 to 2000 micron. Microtrac – Aerotrac could be easily connected to computer with USB and came with its software that directly measured the MVD.
Figure 37 Droplet size calibration curves for Mod-I nozzles

The Aerotrac unit mounted in the cross-section is seen in Figure 39. Due to the size of the instrument, study of spatial distribution of droplet sizes was not possible. The instrument was first installed in the tunnel and the tunnel was brought up to a speed of 10 m/s. After gathering initial data, it was decided to move the system to an open chamber in where a single nozzle was characterized. The decision to characterize the nozzle in an open chamber was related to the difficulties to prevent moisture condensation in the lenses when the unit was placed in the tunnel. During the extensive tests, droplet sizes well beyond Appendix C regime and up to 200 micron were tested. The agreement between the requested and measured MVD is plotted and seen in Figure 40. The observed MVD matched between ±15 percent of the requested MVD for the NASA Standard Nozzles.
The droplets exiting the nozzle are not always perfectly spherical and take somewhat elliptical shape. The diameter hence measured can be, the semi major axis or the semi minor axis i.e. higher or lower than the actual size of the droplets which can explain the higher standard deviation in the sizes.

Figure 38 Microtrac - Aerotrac particle sizing instrument in AERTS Chamber
3.3 Conclusion

According to ARP, for particle sizes below 30 micron, ± 3 micron of deviation is acceptable and up to 50 micron ± 10% of the size is allowable. From the observed results, for particle sizes below 30 micron, the droplet sizes lie within the limit. For particle sizes beyond 30 micron up to 50 micron and beyond until 200 micron, a deviation of ± 15 percent is observed.

A droplet size indicator on the LabVIEW code predicts the particle size. This is predicted based on the air and water pressures recorded at the manifold. The effect of water pump initiating the water pressurization and consequent variations
In the water manifold meant pressure variations which caused wider particle sizes as predicted by the indicator.
Chapter 4

4. Aerodynamic Calibration

The aerodynamic calibration of icing tunnels involves gaging the airspeed and its distribution, turbulence intensity distribution and flow angularity distribution in the cross-section.

4.1 Turbulence Intensity

The turbulence intensity is defined as the variation in the free stream velocity compared to the mean velocity at the same location during the same period of time. Mathematically it is defined as the root mean square (RMS) or one standard deviation of the velocity over average velocity [24].

\[ T.I = \frac{v'}{v_{mean}} \quad Equation \ 23 \]

\( v' \) is the RMS velocity.

Icing wind tunnels inherently have higher turbulence intensities due to lack of flow straighteners, presence of spray bars in flow etc [10]. Flow stabilizers cannot be installed in icing wind tunnels because usually they are placed before the test section and doing so in icing tunnel will cause ice accretion on the flow stabilizers. The turbulence in the icing wind tunnels is also significantly higher compared to turbulence experienced in inflight conditions. A higher turbulence than that actually experienced in flight affects the accuracy of data produced in the wind tunnels. Higher turbulence alters the effective Reynolds number of the flow which changes
multitude of parameters in the trajectory equations giving incorrect results from wind tunnels. The Reynolds number is essential to determine the convective heat transfer coefficient which affects the rate of ice growth in different directions and hence the ice shapes.

Eiffel in 1911 reported the drag coefficient of a sphere in a wind tunnel to be 0.18. Fopple in 1912 reported the drag coefficient of a similar sphere in another wind tunnel to be 0.44. The difference was later discovered due to higher turbulence levels in wind tunnels. To prevent such discrepancy and to ensure the data being collected from the icing tunnels is accurate, the SAE ARP establishes a limit on maximum turbulence intensity acceptable in icing tunnels [30].

4.1.1 Principle of Hotwire Anemometer

SAE ARP 5905 states that for turbulence intensity calibrations, a hot wire anemometer is to be used. Compared to mechanical and other varieties of anemometers, hotwire has a high frequency resolution (up to 1 MHz) hence preferred in turbulence measurements. The hotwire setup consists of a hotwire probe, a probe holder, BNC cables connecting probe holders to anemometer, hotwire anemometer that maintains the temperature of the probe, voltage reader to feed the data into the computer and a computer to record and process the gathered data. Different probe types are available that measure turbulence in one, two and three dimensions simultaneously [24].
The probe can be a wire or film type. The wire can be made by welding thin wires to support or by using the Wollaston wire. A Wollaston wire is a very thin platinum wire, successively run through smaller dies until it reaches about 70 micron or lower embedded in the silver mantle. The silver mantle is etched away by acid before using the probe. The film sensors have a cylindrical quartz or glass core covered with nickel or platinum film which is in turn electrically insulated with a thin quartz or ceramic coating. Most common dimensions are 1.25 mm active length, 50 to 70 micron diameter with less than 0.1 micron of film thickness and about 2 mm of coating. The film type wire used in the calibration procedures is seen in Figure 42.
Figure 42 Film type wire used in the calibration

For a wire probe, due to higher length to diameter ratio compared to film type, has an advantage that the prongs have lower influence of on wire. However, film type sensors has higher mechanical strength and stable calibration due to their higher diameters [32].

The anemometer available today has three different variants operating on similar principle, i.e. Constant Current Anemometer (CCA), Constant Voltage Anemometer (CVA) and Constant Temperature Anemometer (CTA). Constant Temperature Anemometers are widely available and was used in calibration of the icing tunnel. CTA operates on a Wheatstone bridge with the probe being installed on one leg of the bridge. The servo amplifier maintains the bridge in balance. Whenever the probe is inserted in a flow, an increase in the fluid velocity will cause an increase in heat transfer, causing the temperature to drop and hence the resistance of the wire to change. This unbalances the bridge and introduces an
error voltage. This error voltage passes through the servo amplifier which alters the bridge voltage and hence the current which heats the probe wire. The wire is heated back to a preselected high temperature. The temperature is a function of resistance and is defined as ratio of resistances called the Over Heat Ratio (OHR) [32].

The OHR (a) is

\[ a = \frac{R - R_0}{R_0} \quad \text{Equation 24} \]

Where \( R \) is sensor hot resistance

\( R_0 \) is sensor cold temperature (ambient)

Once the OHR is set, the bridge needs to be set in sync with the servo amplifier for optimum performance. This is done by testing the response to a sudden change. Since a sudden change cannot be quantified accurately, a square wave test is used to study the response and have the system in optimum setting. [33]
4.1.2 ARP Guidelines

The SAE guidelines provide a minimum test matrix for aerodynamic calibration. This test matrix includes locations across the cross-section, spray bar air pressures, tunnel static temperatures and test section velocities to calibrate the tunnel. Table 4 Minimum Aerodynamic test matrix [24] describes the recommended test matrix. However, the recommendations may be modified based on the limitations of traverse system, probe accuracy or time limitations [13]. Certain changes were made in the turbulence intensity and flow angularity measurements. The spacing and the range of velocities for both the tests conducted was changed. For the turbulence intensity measurements, tests were carried out at nine locations across for each five rows located transversely. The nine locations were two inches
apart and uniformly distributed. Of the five holes, one was placed centrally and remaining holes are equally spaced on either side. In Figure 44, the circles indicate locations where turbulence intensity tests were conducted in the cross-section.

![Figure 44 Turbulence Intensity measurement locations](image)

**Table 4 Minimum Aerodynamic test matrix [24]**

<table>
<thead>
<tr>
<th>Vertical Position</th>
<th>Horizontal Position</th>
<th>Spray Bar Air Pressure</th>
<th>Tunnel Static Air Temperature</th>
<th>Test section Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, ±25, ±50, ±75</td>
<td>0, ±25, ±50, ±75</td>
<td>Maximum</td>
<td>Ambient</td>
<td>0, 33, 67, 100</td>
</tr>
</tbody>
</table>

It is recommended that aerodynamic tests be carried out at zero, thirty-three, sixty-seven and hundred percent of the test section operating velocities[24]. At the
ambient temperatures, based on power limitations, the maximum speed was of 50 m/s. hence, TI tests were supposed to be carried out at 0 m/s, 17m/s, 34 m/s and 50 m/s. However, for 50 m/s turbulence tests, the probe holder was observed to be vibrating and bending hence needed extra damping and strengthening. The vibrations induce error in turbulence intensity readings by adding a velocity component in the readings which is absent in the flow. Different fixes were attempted for the bending and vibrations. A new design to install the hotwire was prepared but due to space constraints and loss of hotwire, the efforts were stopped.

All the tests were run at least thrice to ensure repeatability of results and to perform uncertainty analysis. The set of three plus tests are run twice, with the cloud making nozzle air on and off. While the nozzle air is on, the air pressure to be used is that that produces smallest droplet MVD. For the current setup, the air pressure used was 30 psi gauge. This pressure produces smallest droplets and mixed phase cloud.

The calibration of hotwire is affected by the surrounding temperature. The velocity calibration changes as the temperature changes however the turbulence intensity measurements remain unaltered due to temperature fluctuations. To ensure the calibration does not change, the tests are run at same total temperature as the temperature at which the anemometer is calibrated. The aerodynamic heating changed the temperature of the tunnel. The heating effect was alleviated by using the tunnel cooling system. The cooling system was automated and temperature was monitored using RTD installed near spray bars. Another RTD was installed
next to hotwire to monitor any temperature changes near the hotwire as seen in Figure 43 [11], [34], [35], [13].

Turbulence intensity is not measured with the cloud turned on as the water droplets colliding with the hotwire cause the voltages to fluctuate heavily which registers higher turbulence than what is actually present. Techniques are being developed to test the turbulence in the cloud. These tests have not shown any significant results to be adopted in current tests [36].

The table below sets the test section performance targets.
Table 5 Performance targets for Turbulence Intensity Tests

<table>
<thead>
<tr>
<th></th>
<th>Measurement Instrumentation</th>
<th>Tunnel Centerline Temporal Stability</th>
<th>Spatial Uniformity</th>
<th>Limit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air OFF</td>
<td>± 0.25 %</td>
<td>± 2 %</td>
<td>&lt; 2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Air ON</td>
<td>± 0.25 %</td>
<td>± 2 %</td>
<td>&lt; 2 %</td>
<td>5 %</td>
</tr>
</tbody>
</table>

Air OFF and Air ON indicate if the cloud making air is flowing through the nozzle. For Air ON the air pressure used was 30 psi (gauge). The tunnel centerline refers to the geometric centerline of the cross section. To establish temporal stability, at least thirty second data history is to be acquired. The spatial uniformity is the maximum variation of turbulence intensity temporal stability from the centerline average temporal turbulence intensity. The limit value is the maximum value of turbulence at any location within the uniform icing cloud area.

4.1.3 Results

4.1.3.1 Velocity Distribution

First, the velocity distribution results are discussed.
At 17 m/s, the maximum deviation was about 5 percent of the value at the center of the cross-section. The highest deviation from the tunnel centerline is observed at the corner at one inch in row five.

Figure 45 Velocity distribution at 17 m/s
At 34 m/s, the maximum variation with respect to centerline velocity is about 8 percent. The standards do not specify any limit on the maximum variation on the velocity from the centerline velocity.

### 4.1.3.2 Turbulence Intensity

Following table describes the test matrix used for turbulence intensity tests.
<table>
<thead>
<tr>
<th>Nozzle Air</th>
<th>Velocity (m/s)</th>
<th>Locations</th>
<th>Repetitions</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>0</td>
<td>5 X 9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>5 X 9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>5 X 9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>OFF</td>
<td>0</td>
<td>5 X 9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>5 X 9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>5 X 9</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

*Table 6 Turbulence intensity test matrix for calibration tests*
Figure 47 Turbulence intensity distribution with 0 m/s velocity and nozzle air OFF

The distribution of turbulence at zero test section velocity without any air blowing from nozzle is shown in Figure 47. The turbulence recorded is a result of draft of the evaporator fan turned on. Figure 48 plots the values of turbulence and compares it with the limits specified in SAE ARP.
Figure 48 Turbulence intensities at 0 m/s and nozzle air OFF

Figure 49 Turbulence intensity distribution 0 m/s and nozzle air ON
The turbulence intensity at zero percent of test section velocity (0 m/s) with air blowing from nozzle at 30 psig is shown in Figure 49. Due to absence of a significant flow in the cross-section and the nozzle air gusting, a higher turbulence is recorded. The values recorded at different locations for the case is shown in Figure 50.

![Graph showing turbulence intensities at 0 m/s and nozzle air ON](image)

*Figure 50 Turbulence intensities at 0 m/s and nozzle air ON*
Figure 51 Turbulence intensity distribution at 17 m/s and nozzle air OFF

Figure 51 represents turbulence intensity distribution for thirty three percent of the test section velocity which at ambient temperature translated to about 17 (m/s) (33 Knot). For all the five transverse points at first point across, a higher turbulence is recorded. The proximity of this test point to the boundary layer, which is unstable caused higher turbulence being recorded. As the test matrix is same for all the tests, this trend is consistent in all tests. Figure 52 turbulence intensities with uncertainty analysis. At thirty three percent with air off, turbulence recorded is
Figure 52 Turbulence intensities at 17 m/s and nozzle air OFF

Higher than the limit of two percent. The higher turbulence at low velocity aids in the uniformity of the cloud giving a wider uniform cloud than reported in the previous chapter.
Figure 53 Turbulence intensity distribution at 17 m/s and nozzle air ON

the turbulence distribution at 17 (m/s) (33 knots) is plotted in Figure 53. The effect of nozzle air is seen on the turbulence levels recorded with slight increase. However, as the ARP limit for turbulence intensity is higher compared to when the air is not blowing and is up to five percent. Majority of the cross-section falls under the limit apart from points closer to the boundary layer.
The distribution of turbulence intensity at sixty even percent of the cross-section velocity with nozzle air off is seen in Figure 55. That translated to roughly 34 (m/s) (66 knot) cross-section velocity at ambient temperatures. The turbulence recorded over the area is lower compared to the 17 (m/s) case but still higher than the limit of two percent. The spread of data is narrower indicating more consistency in turbulence levels. The turbulence dropped from under four percent to under three percent. The turbulence levels in the cross-section can be seen in Figure 56.
Figure 55 Turbulence intensity distribution at 34 m/s and nozzle air OFF

Figure 57 and Figure 58 indicate the turbulence intensity distribution and uncertainty at sixty seven percent of test section velocity (34 m/s) (66 knot) with nozzle air blowing. The effect of nozzle air is seen to be diminishing with the turbulence levels being up to three percent over the cross-section except near the boundary flow.
As the probe holder was unstable above this velocity and the hot wire was damaged, no results are recorded/presented for hundred percent of the test section velocity (50 m/s (97 knot)). Based on the trends for Air ON cases and turbulence levels for sixty seven percent Air ON case, it can be assumed that the turbulence levels at hundred percent cross-section velocity to be under the limits specified.

**Figure 56 Turbulence intensities at 34 m/s and nozzle air OFF**
Figure 57 Turbulence intensity distribution at 34 m/s and nozzle air ON
Figure 58 Turbulence intensities with 34 m/s and nozzle air ON
4.2 Flow Angularity

Measuring the flow angularity is finding the direction of the flow in the cross-section. It is one of the parameters that should be quantified to fully calibrate any wind tunnel. The instrument used to quantify the flow angle is called the five hole angularity probe.

![Five hole angularity probe](image)

*Figure 59 Five hole angularity probe*

The principle of angularity probes / yawmeters is based on finding the static pressures on geometrically opposite points on the surface of an aerodynamically symmetric object like sphere, cone or wedge. The symmetric object or the probe when inserted in the flow can be rotated until a zero-differential pressure reading is achieved and then the angle of the probe can be read with respect to the reference. The other way is to record the differential pressures and calculate the angle of the flow based on calibration curves. The second method is most commonly used and was used in this study.

The instruments used during this experiment was a United Sensors 5-hole three-dimensional probe, Omega PX277 differential pressure transducer with 0 to 10Vdc for 0.18 psi range, Furnace Control FCO332 with a range of 1.45 psi and LabVIEW
voltage readers along with LabVIEW code to record the data. The calibration curves for the probe was provided by the manufacturing company and probe can measure angles between – 20 degrees to 20 degrees. The calibration curve is shown in Figure 61.

![Holes on five-hole probe](image)

*Figure 60 Holes on five-hole probe*

The recommended limits on flow angularity as mentioned by the ARP are as follows
Table 7 Performance target for flow angularity in test section

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Angularity</td>
<td>± 0.25º</td>
</tr>
<tr>
<td>Tunnel Centerline Temporal Stability</td>
<td>N/A</td>
</tr>
<tr>
<td>Spatial Uniformity</td>
<td>± 2º</td>
</tr>
<tr>
<td>Limit Value</td>
<td>± 3º</td>
</tr>
</tbody>
</table>

Adding to the above matrix, since Flow angularity is an Aerodynamic quantity, these tests were run twice, once with cloud making air ON and later with cloud making air OFF and at zero, thirty-three, sixty-seven and hundred percent of tunnel cross-section velocities. The test matrix for the tests was modified due to probe length, space, and strength limitations. Due to the short length of the probe, only half of the cross-section could be covered for flow angularity test. The lack of enough space between the cross-section and the settling chamber fridge prevented installation of the probe on the opposite side. The flow angularity was measured at four points across for the five transverse points. Multiple tests were conducted to check repeatability of the tests and to perform uncertainty analysis.[24]
The test matrix for the flow angularity tests is shown below. The locations where angularity tests were conducted are seen in Figure 62.
Figure 62 Locations of flow angularity measurements

Table 8 Flow angularity test matrix

<table>
<thead>
<tr>
<th>Nozzle Air</th>
<th>Velocity (m/s)</th>
<th>Locations</th>
<th>Repetitions</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>17</td>
<td>4 X 5</td>
<td>3</td>
<td>Ambient</td>
</tr>
<tr>
<td>OFF</td>
<td>17</td>
<td>4 X 5</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

4.2.1 Results

Flow angularity distribution as measured with nozzle air OFF is shown below
Figure 63 Flow angularity distribution with air OFF

The distribution of flow angularity for a part of the test section is seen in above Figure 63. Tests were run at 17 (m/s) and 34 (m/s) showed deviation less than ten percent of the maximum value hence results only for 17 (m/s) are presented. Figure 64 indicates significant area of the cross section lies under the ARP limit of 3 deg.
The distribution of flow angularity with Air OFF is shown in Figure 64. The first row records a higher flow angle since the nozzles are heavily tilted towards that side for a uniform cloud. From Figure 66 it can be observed that for the central portion of the wind tunnel, the flow angle is less than the limit of 3 deg.

*Figure 64 Flow angularity with air OFF*
Figure 65 Flow angularity distribution with air ON
4.3 Conclusion

The wind tunnel exhibits high turbulence at velocities below sixty seven percent of maximum test section velocity or 34 m/s. This higher turbulence can help in improving the cloud uniformity, however the high turbulence may lead to incorrect heat transfer values which can affect the ice shapes produced in the cross-section. At higher velocities, the turbulence falls within the limits specified in the ARP and hence the shapes produced in the cross-section may be accurate.

The flow angle in the test section is between 2.5 and 3.5 degree limits. The magnitude of the flow angle may not be large enough to alter the inertia of the droplets significantly to influence any data.
Chapter 5 Conclusion and Future Work

5.1 Conclusion

Tunnel calibration of Penn State Icing Tunnel (PSIT) was accomplished. Extensive tests have been conducted to obtain a uniform cloud in the vertical test section of the facility. A new setup to hold the nozzles was designed to allow for spray angle control. The new design with goosenecks provides flexibility to increase the area of uniform cloud compared to the previous more rigid arrangement. A uniform cloud of 11 inch X 11 inch has been established at 50 m/s in the test section. The uniformity changes as the distance of cloud evaluation changes from the nozzle location. Current cloud uniformity is tested about nine inch above the lower end of the cross-section. The uniformity degrades as we move towards the bottom turning vanes. The increase in the cloud uniformity as the speed decreases was demonstrated.

The NASA IRT has 102 MOD-I nozzles and 150 Standard nozzles installed for a cross section 108 inch wide and 72 inch high. At 50 m/s, IRT achieves a uniform cloud of 60 inch by 54 inch. The uniform area is under 42 percent of the total cross-section area. Each nozzle is spraying about 51.84 inch$^2$ of the total cross-section area [21]. For PSIT, the uniform cloud covers 30.25 percent of the total cross-section area at the same speed with each nozzle spraying 100 inch$^2$
Liquid Water Content is quantified for two airline pressures of 15 and 20 psig and 20 MVD. The use of higher air pressure beyond 20 psi resulted in formation of ice crystals thus reducing the amount of supercooled liquid water the test section and increasing the amount of ice crystals. Due to the formation of ice crystals, which is unfavorable, to control the LWC, the airline pressure was combined with velocity in the cross-section. LWC from 0.8 g/m\(^3\) to 2.4 g/m\(^3\) can be sprayed in the test section at different velocities. LWC between 0.8 g/m\(^3\) and 1.6 g/m\(^3\) can be sprayed at 50 m/s and higher velocities. LWC up to 2.4 g/m\(^3\) can be sprayed at 40 m/s. For
higher LWC requirements, the speed can be lowered further. The conditions of LWC and MVD that can be sprayed in the cross-section are superimposed on Appendix C LWC chart and shown in Figure 68.

Figure 68 Intermittent conditions covered [3]

Ability to control the MVD of the droplets was explored using a laser Doppler system created by Aerotrac (Microtrac). Droplet MVD sizes up to 200 micron were tested demonstrating the capability of the facility to produce SLD (Supercooled Large Droplets). Beyond 200 MVD the water pressure cannot be maintained constant hence the MVD is not constant. For particle sizes below 30 micron, the standard deviation of about 3 microns was noticed. For particle sizes beyond 30 micron and up to 200 micron, the particle sizes had a standard deviation of 15
percent of target MVD. The deviations might seem higher but can be explained with the following reasons. Laser diffraction itself has an inherent drawback that it does not take into account the volume of the droplet particles but only the size. Also the droplets exiting the nozzle are not always perfect spheres and may exhibit ellipsoidal properties. The above reasons introduce threshold level of uncertainty based on which the results seem accurate.

Turbulence Intensity tests were completed at three (0 m/s, 17 m/s, 34 m/s) of four (0 m/s, 17 m/s, 34 m/s, 50 m/s) different velocities required by the guidelines. Tests were conducted across 45 different locations in the vertical test section. The test locations were changed slightly as allowed in the guidelines. Data was collected at all points for 30 seconds per test hence establishing temporal stability for turbulence intensity tests. Data was gathered at a sampling frequency of 3 kHz.

Turbulence tests are conducted with the nozzle air turned off and nozzle air flowing. At 17 m/s, the turning on of the nozzle air increased the average turbulence levels by 35 percent from 2.4 to 3.2 percent. The effect of turning on of the nozzle air diminished at 34 m/s with .03 percent increase in turbulence levels on average from 2.20 to 2.23. Based on this trend, we can say the turbulence levels at higher test section velocities may be lower provided the wind tunnel is clear. The average turbulence levels though within the limits of the SAE Aerospace Recommended Practices, are higher when compared to turbulence levels encountered inflight.
The tests were repeated multiple times and uncertainty analysis was performed to ensure accuracy of the tests.

Flow angularity tests were conducted using the United Sensors five hole angularity probe and omega and Furness control differential pressure transducers. The initial tests were carried out at 17 m/s, 26 m/s and 34m/s. The change in flow angle was less than 10 percent (0.3 degrees) hence extensive testing was done at a lower speed of 17 m/s. A study that specified flow angularity is not affected by level of turbulence intensity levels in the cross-section justified the decision to run at 17 m/s. Temporal stability was achieved by gathering data at every point for 30 seconds. The tests were conducted without nozzle air and later with nozzle air blowing. On average, the flow angle without air is 2.7 degrees and with the cloud making nozzle air is 3.05 degrees.

Due to the length of the probe and the size of probe holder, only one side could be used to gather data. The cross-section covered for angularity tests was half of the complete area. The guidelines specify a limit of 3 degrees for the flow angle in the cross-section. The flow angle on average in the cross-section is 3.05 degrees.

5.2 Future Work

5.2.1 Cloud Uniformity

To increase the area under uniformity of the cloud, more nozzles can be installed in the spraybar. Based on conclusions above about cloud uniformity, four more nozzles may increase the total uniformity up to forty percent of the total cross-section area.
5.2.2 LWC Improvement

Including the liquid water content factor, the maximum LWC in appendix C conditions is expected to be 4 g/m$^3$. Additional four nozzles will increase the LWC spraying capability of the wind tunnel and cover a wider region of appendix C. Standard nozzles can be changed to MOD – I nozzles to get a lower LWC.

![Figure 69 Extension of cloud conditions using MOD – I nozzles [3]](image)

Figure 69 Extension of cloud conditions using MOD – I nozzles [3]

Capability of the nozzles to produce SLD has been demonstrated. Cloud uniformity and LWC tests for freezing drizzle section of Appendix O can be performed. Freezing drizzle MVD > 40 micron can be tested that has MVD approximately 100 micron. However the maximum LWC including the liquid water content factor is about 0.4 g/m$^3$. Correspondingly fewer nozzles will be required.

To increase the LWC in the current setup, a water heater could be setup and heated water can be supplied. Heated water will change the degree of
supercooling of water once it leaves the nozzles thus prevent crystals at higher water pressure and eventually will increase the LWC of the cloud.
Appendix

Liquid Water Content MATLAB Prediction Code

LWC Determination Code
by: Yiqiang Han 2011, Modified by Jose Palacios 2017

Principle: by equaling the analytical and experimental expressions of Freezing fraction, the only variable: LWC can be determined. This method will use an iteration, firstly substituting the analytical LWC (from the literature or our test plan) to get the freezing fraction, and then obtain the real LWC from the iteration.

initialization

```matlab
clear all;
clc;
close all;
```

Conditions Declare

```matlab
% All cases and equations used here are based on Literature<Evaluation and Validation for the Messenger Freezing Fraction>, NASA/CR-2005-213852; and <Manual of Scaling Methods> NASA/CR

% Load data from file
[filename_old, pathname] = uigetfile('*.dat', 'Pick an data file');
if isequal(filename_old,0)
    disp('User selected Cancel')
else
    file_name = [pathname filename_old];
end

test_case = importdata(file_name);
[d1,d2] = size(test_case.data);
test_case_number = d1;

LWC_loop = zeros(test_case_number,2000);
thickness_loop = zeros(test_case_number,2000);
LWC_temp = zeros(test_case_number,2000);
n_loop = zeros(test_case_number,2000);
n_analytical = zeros(test_case_number,1);
n_hiton = zeros(test_case_number,100);

for num = 1:test_case_number
```
C = test_case.data(num,2);

t_st = test_case.data(num,3);

V = test_case.data(num,4);

MVD = test_case.data(num,5);

LWC_a = test_case.data(num,6);

tau = test_case.data(num,7);

thickness = test_case.data(num,8);

% Leading Edge Radius
% d = 2*1.1019*C*.12^2; % for NACA 00XX airfoil, leading edge radius r =
% 1.1019*c*thickness_percentage^2;
% d = 2*0.0158*C; % For NACA 0012

d = C; % for rod

T_st = t_st+273.15; % free stream static temp/centigrade/K
T_s = 0; T_s = 273.15; % surface temp (for glaze ice)/centigrade/K
T_film = 0.5*(T_s+T_st); % film temp/K. Average of free stream and
surface temp.

r = 1.40; % gamma, ratio of specific heat of air (const
pressure/const volume). Also known as adiabatic index. Cp/Cv
R_a = 287; % air characteristic parameter, or specific
gas constant for dry air (R/mol mass), where R is Boltzmann's constant in units of
energy 8.3144598 J/(mol K)
M_a = V/sqrt(r*R_a*T_st); % Mach # from isentropic flow equation
(appropriate without shock waves, reversible process)

T_tot = T_st*(1+(r-1)/2*M_a^2); % Total temperature/K, stagnation temperature
(includes adiabatic increases)

p_tot = 101490.07; % State College, PA. Total pressure/Pa
(assumed, will vary with altitude)

p_st = p_tot/((1+(r-1)/2*M_a^2)^((r/(r-1)))); % Static pressure/Pa when brought
to rest isentropically from Mach #
deltaT_w = T_st-273.15; % Difference between free stream and assumed
surface temperature
deltaT_ww = T_s-273.15; % ZERO: difference in surface temperature. Assumes perfect insulation by ice formation

% Vaper pressures for water and water (w) at ice surface (ww). Pa
p_w = 610.78+deltaT_w*(44.365+deltaT_w*(1.4289+deltaT_w*(2.6506e-2+deltaT_w*(3.0312e-4+deltaT_w*(2.0341e-6+deltaT_w*6.1368e-9)))));
p_ww = 610.78+deltaT_ww*(44.365+deltaT_ww*(1.4289+deltaT_ww*(2.6506e-2+deltaT_ww*(3.0312e-4+deltaT_ww*(2.0341e-6+deltaT_ww*6.1368e-9)))));

c_p_ws = 4220+0.347*(T_s-273.15); % specific heat at const pressure for water
surface/(J/Kg/K) = 4220 (Energy needed to raise 1 degree C)

rho_w = 1000; % water density/(Kg/m^3)
rho_i = 917; % ice density/(Kg/m^3). Assumed. It will change for different types of ice.

Analytical Part

gamma_f = 334; % latent heat, water freeze/(J/g). Energy released or absorbed during heating process
gamma_v = 2500; % latent heat, water evaporation /(J/g).
phi = T_s-T_st-V^2/(2*c_p_ws); % water drop energy transfer coeff. needed for freezing fraction calculation
c_p_a = 1005; % specific heat at const pressure for air/(J/Kg/K)

k_a_film = (-12.69+2.029*sqrt(T_film))*4.184/3600; % thermal conductivity of air/(W/m/K)

miu_a_st = 1e-4/(0.12764+124.38/T_st); % air viscosity as a function of temperature. Pa s

miu_a_film = 1e-4/(0.12764+124.38/T_film);

Pr_a = c_p_a*miu_a_film/k_a_film/10; % prandtl # with a 1/10 fix
(viscous diffusion/thermal diffusion)

rho_a_film = p_st/R_a/T_film; % air density at film temperature Kg/m^3
rho_a_st = p_st/R_a/T_st; % air density at static temperature Kg/m^3

Re_a_monitor(num) = V*d*rho_a_film/miu_a_film/10; % Reynold # at film temperature; with a 1/10 fix
Re_a_film = Re_a_monitor(num);
Re_a_MVD = V*MVD*rho_a_st/miu_a_st*1e-5; % Reynold # using MVD as characteristic dimension; with a 1e-5 fix

for count = 1:1
correlation_case = 2; %Pick correlation case, 2 based on Anderson and Tsao linear fitting recommended.
count_ne = correlation_case

D_v = 0.21*e-4*(T_film/273.15)^1.94*(101320/p_st); % Diffusivity of water vapor m^2/s

Sc_a = miu_a_film/rho_a_film/D_v/10; % Schmit #; (momentum diffusivity or viscosity to mass diffusivity) with a 1/10 fix

if Re_a_film>1e5
   Nu_a = 1.10*Re_a_film^0.472; % Nusselt #, dimensionless (selected from Manual of Scaling Methods)
else
   Nu_a = 1.14*Pr_a^0.4*Re_a_film^0.5;
end

h_c = k_a_film*Nu_a/d*100; % film convective heat transfer coefficient; W/(m^2 K) with a 100 fix
h_G = h_c/c_p_a*(Pr_a/Sc_a)^0.67*1000; % Gas phase mass transfer coefficient kg/(s m^2)
\[ \theta = T_s - T_{st} - V^2/(2c_p(a)) + h_G/h_c*gamma_v*(p_{ww}/T_{st} - p_{tot}/T_{tot}/p_{st})/(1/0.622*p_{tot}/T_{tot}-p_{ww}/T_{st}); \] % air energy transfer coeff.

\[ \lambda_{fraction} = 1/(0.8388+0.001483*Re_a_{MVD}+0.18478*sqrt(Re_{a_{MVD}})); \] % lambda/lambda stokes: drop range parameter/dimensionless

\[ K = \rho_w*MVD^2*V/(18*d*\mu_{a_{st}})/1e9; \] % Inertia parameter, with a 1e-9 fix
\[ K_0 = 0.125+\lambda_{fraction}*(K-0.125); \] % Modified inertia parameter, for trajectory analysis
\[ \beta_0 = 1.40*(K_0-0.125)^0.84/(1+1.40*(K_0-0.125)^0.84); \] % local catch efficiency, or collection efficiency, fraction of the original water content that actually impacts the model is the local catch efficiency

%Set first plot with error bars +/- 15% wrt LWC_a. ~= NOT EQUAL
if LWC_a = 0
 figure(count)
 hold on; grid on;
 colormap summer
 bar(num,1.15*LWC_a,'BaseValue',0.85*LWC_a,'ShowBaseline','off');
 alpha 0.3 % Change the color scheme
 plot(num,LWC_a,'-b*');
end

First loop begins here

error_thickness = 1;

eps = 0.001; %incremental LWC
k = 1;
LWC_hiton(num) = 0;

iter = 9000; %pick number of iterations. Increase if matching is not accomplished
for i = 2 : iter
 LWC_loop(num,i) = LWC_loop(num,i-1)+eps;

 b = LWC_loop(num,i)*V*beta_0*c_p_ws/h_c/1000; % relative heat factor; with a 1/1000 fix
 Ac = LWC_loop(num,i)*V*tau/(\rho_i*d)*6;
 n_loop(num,i) = (c_p_ws/gamma_f)*(phi+theta/b)/1000; % Analytical freezing Fraction
 if n_loop(num,i)>1
 n_loop(num,i) = 1;
 end

Testing different thickness correlations

if count_ne == 1
 thickness_loop(num,i) = n_loop(num,i)*Ac*beta_0*d;

if count_ne == 2
 thickness_loop(num,i) = (0.0184+1.107*n_loop(num,i))*Ac*beta_0*d;
%correlation 1; EXPERIMENTAL RELATIONSHIP BETWEEN FREEZING FRACTIONS
else if count_ne == 3
 thickness_loop(num,i) = (-0.0013+1.124*n_loop(num,i))*Ac*beta_0*d;
%correlation 2
else if count_ne == 4

thickness_loop(num,i) = (-0.0236+1.263*n_loop(num,i))*Ac*beta_0*d;

end
end

error_thickness = (thickness_loop(num,i)-thickness);

Plot data

if n_loop(num,i)<=1
    if (thickness_loop(num,i)>0 && abs(error_thickness)<0.1)
        if (abs(error_thickness)/thickness<0.005)
            hold on; grid on;
            plot(num,LWC_loop(num,i),'-rs');
            legend('error bar, +/-15% of LWC_a','Target LWC','LWC_e based on EXP measurement','location','southeast');

            LWC_hiton(num) = LWC_loop(num,i);
            LWC_temp(num,k) = LWC_loop(num,i);
            n_hiton(num,k) = n_loop(num,i);
            thickness_hiton = thickness_loop(num,i);
            k = k+1;
        end
    end
end
endif LWC_hiton(num) == 0
    display([strcat('Test Case Number__',int2str(num),' failed to match the thickness')]);
    continue;
else
    figure(count)

    hold on; grid on;
    xlabel('Test Case Number');
    ylabel('LWC');
    LWC_midpoint(num) = LWC_temp(num,ceil(k/2));

    % output data to file
    %[file,path] = uiputfile(strcat('output_test___',int2str(num)),'Save file name');
    %filename = [pathname 'output_' filename_old];
    %fid = fopen(filename,'a+');

    output to file........

    %fid = fopen(file_name,'a+');
    %fprintf(fid,strcat('

 Test Case Number__',int2str(num),'
'));
    %fprintf(fid,'LWC_code = %6.3f  LWC_max = %6.3f  LWC_min = %6.3f
',LWC_hiton(num),LWC_temp(num,k-1),LWC_temp(num,1));
    %fprintf(fid,'freezing fraction code is %4.3f  thickness code is %4.3f cm
',n_hiton(num,niyeyede-1),thickness_hiton);
    %fclose(fid);
end
end
end
end
References


November, 2008.


