DESIGN, FABRICATION, AND EVALUATION OF A PARTIALLY MELTED ICE PARTICLE CLOUD FACILITY

A Dissertation in Aerospace Engineering

by

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Abstract

High altitude ice crystal clouds created by highly convective storm cells are dangerous to jet transport aircraft because the crystals are ingested into the compressor section, partially melt, accrete, and cause roll back or flame out. Current facilities to test engine particle icing are not ideal for fundamental mixed-phase ice accretion experiments or do not generate frozen droplet clouds under representative conditions. The goal of this research was to develop a novel facility capable of testing fundamental partially melted ice particle icing physics and to collect ice accretion data related to mixed-phase ice accretion. The Penn State Icing Tunnel (PSIT) has been designed and fabricated to conduct partially melted ice particle cloud accretion. The PSIT generated a cloud with air assisted atomizing nozzles. The water droplets cool from the 60psi pressure drop as the water exited the nozzle and fully glaciate while flowing in the -11.0°C tunnel air flow. The glaciated cloud flowed through a duct in the center of the tunnel where hot air was introduced. The temperature of the duct was regulated from 3.3°C to 24°C which melted particle the frozen particle from 0% to 90%. The partially melted particle cloud impinged on a temperature controlled flat plate.

Ice accretion data was taken for a range of duct temperature from 3.3°C to 24°C and plate temperature from -4.5°C to 7.0°C. The particle median volumetric diameter was 23µm, the total water content was 4.5 g/m³, the specific humidity was 1.12g/kg, and the wet bulb temperature ranged from 1.0°C to 7.0°C depending on the duct temperature. The boundaries between ice particle bounce off, ice accretion, and water run off were determined. When the particle were totally frozen and the plate surface was below freezing, the ice particle bounced off as expected. Ice accretion was seen for all percent melts tested, but the plate temperature boundary between water runoff and ice accretion increased from 0°C at 8% melt to 3°C at 90%. There were two types of ice accretion with a transition zone in between. The first type of ice was opaque in color and
had a rough surface. This ice occurred roughly from 6.0°C to 12.0°C duct temperatures (8% to 50% melt). The qualitative characteristics of the ice were produced from the low water content in the cloud. The water that was available froze instantly and trapped ice particle. Duct temperatures greater than 17.5°C (80% melt) produced ice that was clear and smooth. The water in the surface did not freeze instantly due to the high water content creating a water film that froze.

A mixed-phase cloud dynamics model from NASA Glenn was used to estimate the percent melt of the cloud exiting the duct. There was no way to validate the model by directly measuring the percent melt of the cloud, so single particle melt experiments were conducted and compared to the model. A 0.05g/L solution of rhodamine b was sprayed into a levitator and droplets formed at the nodes of the wave. A 532nm green laser was used to illuminate the dye, and the water emitted orange 593nm light given the luminescent properties of the ink. The emitted light intensity was recorded, and a linear relationship between the light intensity of ice to the light intensity of water was used to determine the percent melt of a droplet. The droplets were frozen with a cold flow of nitrogen gas via a liquid nitrogen heat exchanger. The droplets melted under natural convection when the cold nitrogen was shut off. Fifteen cases were compared with droplet diameters ranging from 324µm to 1112µm, air temperatures from 16°C to 31°C, and relative humidities from 41% to 100%. The average discrepancy between predictions and results for the cases that melted slower than ten seconds was 13% while the cases that melted faster than 10 second had 64% discrepancy between the model and experiment. To explain the discrepancy between the experiment and model, sensitivity studies of the model were conducted. It was seen that the melt time from the model was most sensitive to ambient temperature (1s/°C). It was also seen that the thermistors used in the experiment were accurate to 0.7°C. Transient effects of the rhodamine b caused an overshoot in light intensity, making it difficult to accurately determine the melting stop time. These factors led
to the difference in melt time between the model and experiments. A 2.7s difference between model and experiments was deemed to be a successful correlation between predictions and experimental results given the model sensitivity to temperature, the difficulty in measuring temperatures at the position of the droplet, and the transient characteristics of rhodamine b.
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Nomenclature

A – area
Bi – Biot number
Cd – drag coefficient
Cf – flow rate coefficient
Cp – particle specific heat capacity
D – particle diameter
g – gravitational acceleration
h – heat transfer coefficient
hm – mass transfer coefficient
Hp – particle enthalpy
kair – air thermal conductivity
kp – particle thermal conductivity
Levap – latent heat from evaporation
\( \dot{M} \) – mass flow rate
mair – air mass
mp – particle mass
MR – mixing ratio
Nu – Nusselt number
P – pressure
Ps – static pressure
Plw – particle vapor pressure at the wet bulb temperature
ppt – parts per thousand
Pr – Prandlt number
qconv – convective heat transfer
qlatent – latent heat due to mass transfer
Ra – Rayleigh number
RH – relative humidity
SH – specific humidity
Stk – Stokes number
SVP – saturation vapor pressure
SVP\textsubscript{e} – estimated saturation vapor pressure
t – time
t\textsubscript{0} – relaxation time
T\textsubscript{air} – air temperature
T\textsubscript{p} – particle temperature
T\textsubscript{\infty} - far field temperature
T\textsubscript{surf} – particle surface temperature
T\textsubscript{w} – wet bulb temperature
V – velocity
V\textsubscript{air} – air velocity
V\textsubscript{p} – particle velocity
VP - vapor pressure
VP\textsubscript{e} – estimated vapor pressure
\dot{W} – volume flow rate
\alpha – diffusivity
\beta – thermal expansion coefficient
\delta – number of nozzles
\rho\textsubscript{air} – air density
\rho\textsubscript{p} – particle density
\theta – pressure compensated melt potential
\mu\textsubscript{g} – gas dynamic viscosity
\nu – kinematic viscosity
\omega\textsubscript{air} – air vapor mass fraction
\omega\textsubscript{p} – particle vapor mass fraction
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1. Introduction

Aircraft have been encountering in-flight icing conditions since the advent of flight instrumentation in the mid-1920s. Instrumentation allowed pilots to fly in low or no visibility conditions. The U.S. Air Mail Service pilots were the first to encounter in-flight icing while flying between New York and Chicago. They reported icing to be the most dangerous part of their job[1]. The ice accreted on the airframe and propellers of early aircraft. The physics behind airframe and propeller icing is identical and has been rigorously studied since the late 1920s. Super cooled water droplets impinge on the leading edge of airfoils and run aft as a thin film of liquid. The water freezes to the leading edge, degrading the performance of the airfoil. Modern jet transport aircraft still encounter airframe icing, but radar and ice protection systems keep passengers and pilots safe from airframe icing.

Engine icing has emerged as a new threat to jet aircraft. Since the 1990s, at least 240 engine power loss events have occurred due to engine icing. Commuter jets operating between 28,000 ft (8.53 km) and 31,000 ft (9.45 km) and near adverse weather reported engine power would decay, known as rollback. The fan could slow down to sub-idle speeds and the turbine gas temperature would increase until the pilot shut the engine down. When the pilots descended below 10,000 feet (3.05 km), the engines that were still running regained full power and the engines that had been shut down were able to be restarted. At the time, the cause of the power loss was a mystery. Large transport aircraft also experienced rollback near convective clouds but at high altitudes where no liquid water could exist. The aircraft were flying in a region of low radar reflectivity and turbulence, up and away from the storm cell. Hail was not suspected because there was no airframe damage to the aircraft[2].
It is now widely accepted that ice particles at high altitude are the cause of engine rollback. Large convective storm cells push moisture high into the atmosphere, where it freezes into small ice particles. Radar is not able to see the particles. There are no visual indications since the ice will not freeze to the airframe, making this icing condition difficult to detect[3]. The current theory of engine core icing is that ice particles at high altitude are ingested into the compressor section of an engine, where the particles will partially melt and accrete on the stators. The ice accretion blocks airflow, causing rollback. With limited understanding of the engine core icing phenomenon, the only method of mitigation and prevention is to infer from storm cells where regions of ice particles may be and avoid them. Aircraft with engines that have been flagged as susceptible to icing are recommended to avoid convective storm cells by 50 nautical miles (92.6 km) and fly up wind of the cell if possible[3].

Both NASA and the National Research Council of Canada (NRC) are heavily investing in engine icing research. NASA has modified the Propulsion Systems Laboratory (PSL) at NASA Glenn with the addition of air assisted atomizing water nozzles. These are the same nozzles used in the NASA Glenn Icing Research Tunnel. The updated PSL can reproduce flight conditions for engines from 4,000 ft (1.22 km) to 40,000 ft (12.2 km), air speeds from Mach 0.15 to 0.8, and temperature from 45 °F (7.2 °C) to -60 °F (-56.7°C). It can generate super cooled droplets and ice particles with particles sizes from 40 to 60 µm and cloud densities from 0.8 to 9.0 g/m³[4]. The NRC has also modified its open circuit altitude test facility. The NRC facility uses atomizing nozzles to create water drops between 20 and 40 µm and cloud densities from 0.5 to 4.0 g/m³. Unlike the PSL, the NRC facility makes ice particles by grinding blocks of ice. The diameter of the ice particles are between 100 and 300 µm with cloud densities from 2 to 10 g/m³[5]. Although
the NASA PSL and NRC altitude test facility are impressive, they are both expensive to run and do not focus on fundamental physics.

1.1. Atmospheric Conditions

1.1.1. Engine Icing Event Statistics

Mason et al. evaluated the flight data from 46 engine icing incidences in search of patterns from the events. The 46 flights were chosen out of the 240 known incidences because those flights had more complete data to evaluate. The locations for the icing events group together in 4 regions around the world (see Figure 1-1). The locations, in order of engine icing frequency, are: the Asia-Pacific region from Australia to Korea; across North America between the Caribbean and Canada; Central Europe; and near Buenos Aires, Argentina. At first glance, the icing event location data looks like a density map of air traffic, making the location of the events insignificant. With a more thorough inspection, however, it can be seen that this is not exactly the case.

![Figure 1-1: Locations for engine icing incidences [2]](image)

Figure 1-2 is a map of flight paths and destinations. Europe undoubtedly has the busiest air traffic, followed by the USA, East-Asia, and South America. If the icing event locations only correlated with flight density, Europe should have the highest incidence; however, the Asia-Pacific Region
has the highest incidence. After giving the data a closer look, an important pattern arises from the event locations: all of the icing events happened in regions of frequent strong storm cells.

![Figure 1-2: Flight paths and destinations [6]](image)

In addition to geographic location, there was a pattern in altitude and ambient temperature when the engine icing event occurred. Most importantly, the vast majority of the events occurred outside of the FAR Part 25 appendix C Icing envelopes[7], as seen in Figure 1-3. The altitude of the incidences was biased toward higher altitudes, and most of the incidences occurred at temperatures warmer than the International Standard Atmosphere (ISA). The engine icing events seem to band between 10,000 ft (3.05km) and 40,000 ft (12.19 km) and ISA+10 and ISA+20. It was also noted that aircraft total air temperature sensors would malfunction and read warmer than expected due to ice particle contamination [2].
Figure 1-3: Altitude and temperature envelopes for engine icing events and FAR Part 25 appendix C Icing envelopes [2]

Of the 46 cases studied, one flight had power loss during takeoff, 17 had power loss in cruise, and 28 had power loss in descent. It is believed that engines are more vulnerable during descent because the engines are operating at a low power setting. The compressor temperature decreases, leaving it more susceptible to ice accretion. During cruise, the engines are operating at higher power, but the ambient temperature is lower and most of the ice particles populate the upper atmosphere. Take off has the least number of incidences because the engine is warmer due to lower altitudes and full power setting for the engine. The incidences also correlated with the seasons. In the northern hemisphere, the number of events increased though the spring, peaking in June then decreasing through autumn. A similar trend was seen in the southern hemisphere with the number of incidences peaking in January. Mason et al. made a list of nine commonalities in the engine icing events [2]:

5
• high altitude/cold temperature
• flying near convective clouds
• significantly warmer conditions than ISA
• visible moisture or in a cloud
• light turbulence
• precipitation on wind screen
• TAT anomaly
• no observations of airframe icing
• no flight-radar echoes at the location and altitude at the time of the event

1.1.2. Convective Cloud Physics

A pocket of warm moist air will convect up into the atmosphere, creating a cumulus cloud as the moisture condensates due to cooler temperatures at higher altitudes. As the water condensates, heat is released, pushing the cloud higher and increasing the updraft strength and cloud size. The water in the cloud will remain liquid until it convects above the freezing line, then the liquid will become supercooled or freeze into ice particles. The moisture will condense until it falls out of the cloud as precipitation, creating a competing down draft. The cloud will increase in height until it reaches the troposphere. Then, it fans out into an anvil shape. The cloud will decay when the down drafts dominate the cloud. The cloud will become glaciated when the supercooled water freezes into ice particles. Glaciation starts in the anvil, which becomes the dominate structure[8]. See Figure 1-4 for a diagram of a convective cloud life cycle.
Storms with very strong convection can develop into supercells. The updraft is so strong in supercells that they can push moisture up above the troposphere and create a structure called the overshoot. See Figure 1-5 for a supercell diagram and Figure 1-6 for a photograph. Supercells can draw moisture up to 40,000 ft (12.19 km) into the atmosphere[8].
1.2. Ice/Water Content in Clouds

A cloud system has very dynamic aero-thermodynamics convecting warm moist air high up into the atmosphere where the moisture can fan out, cover a large area in the upper atmosphere, and freeze into ice particles. Understanding the liquid water content (LWC), ice water content (IWC), and total water content (TWC) in the anvil region of high convective clouds is key to understanding the engine core icing phenomenon. Researchers have flown airplanes outfitted with particle sensors through storm clouds around the world. “Cloud Particle Measurements in Thunderstorm Anvils and Possible Weather Threat to Aviation” by Lawson will first be reviewed in-depth, because the author covers a wide range of storms in one article[11]. Then, a summary of work done by other researchers will be presented to show the spread in data for ice particle properties.

National Center for Atmospheric Research (NCAR) researchers have performed flight tests though storm systems over Montana during the Cooperative Convective Precipitation Experiment
(CCOPE) and tropical storms in the Central Pacific Ocean between Papua New Guinea and Hawaii during the Central Equatorial Pacific Experiment (CEPEX). During the CCOPE tests, data on particle size, concentration, and IWC were taken though the anvil at altitudes from 6.5 km to 9.5 km. The particle size detector had a minimum resolution of 300 µm. Particles smaller than 300 µm were not captured and could not be counted for analysis. The particles were not all spherical in nature so the maximum dimension was analyzed. The range of particle sizes seen in storm clouds over Montana was 11 mm to 300 µm with most of the particles falling between 6.0 mm and 300 µm uniformly. At 6.5 km the particle concentration ranged from 0 to 20 particles/L and at 9.5 km the range was 0 to 42 particles/L. The maximum concentration was seen at 9.3 km. At all altitudes, the particle concentrations were biased to the low end. The IWC ranged from 0 to 2.5 g/m³ from 6.5 km to 7.7 km, then the maximum IWC decreased linearly to 1.3 g/m³ at 9.5 km. Analyzing the change in IWC from the peak IWC out to the edge of the cloud, it was seen that a higher peak correlated with faster decay. When the IWC peak was 2.5 g/m³, the IWC decayed linearly at a rate of 0.11 g/(m³ km), reaching 0 g/m³ at 23 km away from the peak. When the IWC peak was 1.5 g/m³, the IWC decayed linearly at a rate of 0.04 g/(m³ km) reaching 0 g/m³ at 35 km. When the IWC peak was 0.5 g/m³, the IWC decayed linearly at a rate of 0.02 g/(m³ km) reaching, 0 g/m³ at 30 km away from the peak[11].

For the CEPEX testing, the storm cells were banded together in the chain, and the anvil was located at high altitudes due a higher troposphere in the tropics. Data was collected from altitudes of 8.0 km to 14.5 km. The aircraft did not fly through individual cells but flew down the length of the system and never left the cirrus cloud system. The tropical storms had particle sizes ranging from 37 µm to 7.2 mm at 8.0 km and 37 µm to 2.5 mm at 14.0 kms with the maximum particle size decreasing linearly with altitude. The sensor used for the flight tested had a 35 µm
resolution, so any particle smaller than 35 µm would be missed. The particle concentration ranged from 0 to 1500 particles/L at all altitudes surveyed, and the data was biased to the low concentrations. The IWC range at 8.0 km was 0 to 1.7 g/m³ and at 14.0 km was 0 to 1.0 g/m³ with the maximum IWC decreasing linearly with altitude. A similar trend in LWC decay was seen in the tropical storms. When the IWC peak was 1.7 g/m³, the IWC decayed linearly at a rate of 0.012 g/(m³ km) reaching 0 g/m³ 140 km away from the peak. When the IWC peak was 1.4 g/m³, the IWC decayed linearly at a rate of 0.01 g/(m³ km), reaching 0 g/m³ at 140 km. When the IWC peak was 0.5 g/m³, the IWC decayed linearly at a rate of 0.003 g/(m³ km), reaching 0 g/m³ at 200 km away from the peak[11].

It is difficult to compare the tropical storms to the continental storms because the sensors used in the tropics were much more sensitive. Even with this limitation, the highest IWC regions of both the tropical and continental storms were dominated by particle sizes around 2mm. IWC and particle concentration correlated positively. The tropical storms had much higher concentrations due to the smaller resolution in the sensor. It was noted that only super cells and complex thunder storms were able to generate IWCs greater than 1 g/m³ outside of the core[11].

Many other people have studied cloud microstructure since the 1970s. Their contributions will now be reviewed and their data has been summarized in Table 1-1. Knollenberg studied thunderstorm anvils in the tropics. The IWC he recorded, 0.03 g/m³, is significantly less than the other researchers[12]. In 1990, Richard Jeck compiled ice particle data taken across the USA to make a database of ice particle properties in clouds. Data was taken from 50 flights through cloud types including snowstorms, cirrus, thunderstorm anvils, and stratiform[13]. Jeck later proposed ice/snow test specifications for in-flight conditions for the Federal Aviation Administration (FAA)[14]. Andrew Detwiler studied anvils of convective clouds in the US High Plains region.
The particle sensor used had a resolution of 33 µm, but it undercounted particles smaller than 50 µm[15].

Table 1-1: Summary of ice particle characteristics in storm cells († - tropical, ‡ - continental, * - mean)

<table>
<thead>
<tr>
<th></th>
<th>IWC Max (g/m³)</th>
<th>Particle Size Range (mm)</th>
<th>Particle Concentration Max (Parts/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lawson et.al. [11]</td>
<td>2.5†/1.5†</td>
<td>0.3-11.0†/0.03-7.2†</td>
<td>150†/1500†</td>
</tr>
<tr>
<td>Knollenberg et.al.[12]</td>
<td>0.03†</td>
<td>0.05 -1.3†</td>
<td>30.0†</td>
</tr>
<tr>
<td>Jeck et.al. [13]</td>
<td>2.8‡</td>
<td>0.1-10.0‡</td>
<td>400‡</td>
</tr>
<tr>
<td>Detwiler et.al. [15]</td>
<td>--</td>
<td>0.05-4‡</td>
<td>1000‡</td>
</tr>
<tr>
<td>Heymsfield et.al.[16]</td>
<td>0.15†*</td>
<td>0.3-1.1‡</td>
<td>150‡</td>
</tr>
<tr>
<td>Heymsfield et.al. [17]</td>
<td>0.95‡</td>
<td>0.1-2.7‡</td>
<td>30‡</td>
</tr>
</tbody>
</table>

Andrew Heymsfield et.al. has published many papers on cloud microstructure while working for NCAR. Heymsfield et.al. also worked on the CCOPE investigating ice particle growth in the anvil region of storms[18]. The data from CCOPE was compiled and relationships for the IWC in thunderstorm anvils were derived [19]. In 1986 over Wisconsin, extensive data was collected on cirrus clouds, including ice particle morphology (see Figure 1-7), IWC, particle concentrations, and LIDAR scans[17]. In earlier work, Heymsfield et.al. published data from seven flight tests, taking data through the different sections of thunderstorms and comparing IWC measurements to radar reflectivity[16]. In addition to convective clouds, Heymsfield et.al. studied cirrus clouds over Oregon and Connecticut[20]. The biggest limiting factor to all of this previous research is the inability to account for particles smaller than ~50 µm. The smallest ice particle size is still unknown. If smaller particles do exist, their involvement in engine icing will have to be investigated.
1.3. Engine Icing Experiments

1.3.1. Test Facilities

There are two facilities capable of running experiments to understand the engine icing phenomenon. The cascade rig at the National Research Council (NRC) of Canada’s Research Altitude Test Facility (RATFac) and the NASA Glenn Propulsion Systems Laboratory (PLS). The RATFac has been used extensively to test engine components and the PSL can test small and mid-size engines.
The RATFac, as seen in Figure 1-8, has the capability to spray liquid water at a controlled MVD and LWC and inject solid ice particles into the flow. The mix of ice and water is ingested into the test section, where ice accretion of engine components is tested. The ice particles are created by grinding flaked ice down to representative sizes. The ice flakes, ranging from 2.54 to 25.4 mm, are ground then screened to filter the maximum and minimum particle sizes. The grinder produces particles with a median mass diameter (MMD) from 100-300 µm, as seen in Figure 1-9. 200kg of ice is available for a single test. The grinder can produce an IWC from 2 to 10 g/m$^3$. The particles are seeded into a jet with airspeeds ranging from 50-90 m/s and temperatures from -15 to -10 °C to match the conditions in the wind tunnel. 8 nozzles are oriented around the ice jet exhaust to spray water. The nozzles produce water droplet sizes from 20 to 40 µm and have a maximum LWC of 3 g/m$^3$[21][22].
A high-speed camera and LED were set up at the exit of the ice injection duct to image the particles to determine the ice particle size. The minimum exposure time to minimize the blur of the particle moving at 85 m/s was 300-100 ns. This was an issue because the minimum exposure time of the camera was only 1 µs. To decrease the exposure time, the LED was triggered 700-900 ns after the camera shutter opened. The lenses had a shallow focal depth, so many of the particles captured were not in focus. An algorithm was developed to determine if a particle was in focus by searching for steep gradients, as seen in Figure 1-10. A steep gradient corresponded to the edge of an in focus particle.

![Figure 1-9: Sample ice particles from RATFac grinder [22]](image1.png)

![Figure 1-10: Post processed image for particle detection [23]](image2.png)
The NASA Glenn PSL Test Cell 3 has been modified to produce ice particle and mixed phase clouds, as seen in Figure 1-11. 110 standard and 112 Mod1 nozzles were added to the plenum. The MVD ranges from 40-60 µm and the TWC ranges from 0.5 – 9.0 g/m³. The PSL can produce pressure altitudes from 1.22 to 12.2 km, total temperatures from -51 to -9 °C, Mach Numbers from 0.15 to 0.8, and air flow rates from 4.5 to 150 kg/s[24]. The PSL has been outfitted with a light extinction tomography system to monitor the icing cloud during testing. To calibrate the tomography system, a laser sheet imaging system was set up at the exit of the tomography duct. The light intensity captured by the laser sheet imaging system was calibrated with a multi-wire TWC probe to correlate light intensity to TWC.

![Figure 1-11: Modified PSL Schematic [4]](image)

The tomography system was constructed from 60 laser diodes and 120 fiber optic detectors spaced evenly around the duct. The fiber optics terminated at a CCD camera where all the channels could be recorded simultaneously. The light from the lasers fanned out at an angle of 300°, so not every sensor could see every laser, as seen in Figure 1-12. The lasers were pulsed sequentially around the duct and data was saved for each pulse individually. Tomography reconstruction
calculated the quantity of interest, in this case LWC, by the fact that attenuation of the light source is proportional to the line integral of the LWC along the path.

Figure 1-12: Projection of 6 lasers to the corresponding sensors [4]

The tomography system and laser sheet system correlated well with each other and the TWC probe. As seen in Figure 1-13, the TWC probe collected data at the center of the duct, and the bulk TWC was measured by integrating over the circle imposed over the TWC map. The percent difference between the bulk TWC for the laser sheet and the tomography system for the case shown was 0.04%. The percent difference in the max TWC was 4.16% and the ratio of the bulk TWC to the probe was 74% for both systems. The tomography system will be able to measure the cloud during testing where no other type of sensor can[4].

Figure 1-13: Comparison of laser sheet, tomography, and TWC probe [4]

<table>
<thead>
<tr>
<th></th>
<th>TWC Circle Diameter</th>
<th>Robust Probe TWC</th>
<th>Bulk TWC</th>
<th>Max TWC</th>
<th>Bulk/Robust Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomography</td>
<td>23.6°</td>
<td>3.295</td>
<td>2.439</td>
<td>3.587</td>
<td>74.0%</td>
</tr>
<tr>
<td>Laser Sheet</td>
<td>23.6°</td>
<td>3.295</td>
<td>2.440</td>
<td>3.743</td>
<td>74.1%</td>
</tr>
</tbody>
</table>
1.3.2. LWC/IWC Measurements Used at PSL and NRC

A multi-wire hot-wire from Science Engineering Associates (SEA) was used as the standard technique to measure IWC and LWC in both facilities. Separate research was conducted in the RATFac to evaluate the accuracy and robustness of the probe in a mixed-phase environment. The SEA probe has three elements, as seen in Figure 1-14. The top and bottom elements have cylindrical cross sections with diameters of 2.1mm and 0.5mm respectively and are designed to measure LWC. They are maintained at temperature of 140 °C, and the power required to maintain that temperature is related to the impinging liquid. The middle element has a half-pipe “c” cross section with the opening upwind to capture all the ice and water to measure TWC. It is maintained at 140°C, but it was seen that it measures lower than expected TWC due to heat of fusion for ice, or particle splashing and bouncing. The half-pipe element only measured 48.5% of the IWC and the two cylindrical elements gave a false reading of 4-5% due to impinging ice particles. Tests were conducted in IWC and LWC only conditions to calibrate the sensor. The TWC, IWC, and LWC were calculated by iterating a set of equations that account for the error from the sensor[23].

Figure 1-14: SEA probe elements [23]
1.3.3. *Compressor Transition Duct Accretion Experiments at NRC*

There is a small range of temperatures where mix-phase ice accretion can occur in an engine. The exit of the booster stage in the low pressure compressor of a turbofan was the first area investigated because it can be cooled by the air flow and the outer wall faces upstream, increasing the likelihood of particle impacts. The base plate could be heated or cooled to simulate the effect of bypass air (1). The variables of interest for the tests were air temperature, dynamic pressure, IWC, ice particle MMD, and base plate temperature. The IWC was monitored with a multi-wire hot-wire probe, and the ice accretion was monitored with real-time video camera, a 250 frames/s high-speed video camera, and a 32,000 frames/s high-speed camera[25].

![Experimental transition duct and representative location in engine](image_url)

*Figure 1-15: Experimental transition duct (a) and representative location in engine (b) [22]*
Ice was accreted for a range of times between 300 seconds and 10 minutes. One test was conducted with the base plate and air temperature below freezing to verify ice particles would not accrete to subfreezing surfaces. Then tests were run with warm air and varied plate temperature. When the air temperature was set at 15°C and the plate was set to -1°C, ice formed on the leading edge of the airfoil and at the corner between the airfoil and the plate, as seen in Figure 1-16. After 1.5 minutes, the ice on the airfoil shed, leaving behind the accretion in the corner. Over time, slushy ice accumulated in front of the base plate. The slush flowed down stream and accreted a large ice mass where the shed ice had left behind an anchor point. For the next test, the air temperature was maintained and the plate was heated to 5°C. Ice accreted on the leading edge of the airfoil in the same manner but did not accrete on the base plate at first. The same slushy ice flowed across the bottom of the test section, eventually lodging in the corner between the plate and the airfoil. The slushy ice had built up across the whole width of the test section after 5 minutes. In the last test, the dynamic pressure was increased and the IWC was decreased to separate the effects of impinging ice and water flowing down the test section. At this test condition, no ice built up in the end wall, so it was shown that the amount of melting that takes place in the air affects the accretion at the wall[25].

Figure 1-16: Ice accretion after 5 min (T_{air} = 15 °C & \ T_{plate} = -1 °C) [25]
The next set of tests conducted searched for the air temperature bound where ice accretion was possible. It was found that between 15˚C and 20˚C air temperature is one side of the ice accretion boundary. At 20˚C, ice accreted on the leading edge of the airfoil and only a 3mm sized formation was seen in the corner. At 15˚C, ice accreted and shed from the leading edge and more ice built up in the corner. The decrease in air temperature reduced the amount of melting and the initial surface temperature. The effect of IWC was also studied, and it was seen that the accretion for a given accretion time increased non-linearly with IWC [25].

1.3.4. Airfoil Accretion Experiments at NRC

NASA, NRC, and the Ohio Aerospace Institute tested a wedge airfoil in the RATFac to measure ice accretion rate as a function of air speed, ambient temperature, wet bulb temperature, relative humidity, IWC, and LWC. A model of the airfoil can be seen in Figure 1-17. Wet bulb temperature ($T_{wb}$) is the temperature of air if it would be cooled to full saturation. It is a function of the dry air temperature, pressure, and relative humidity. At a wet bulb temperature greater than 0˚C, the particles on the surface of a body will gain heat from the surface and melt, and at a wet bulb temperature below 0˚C, the particles will lose heat to the surface and could freeze. The test section was instrumented with a multi-wire hot-wire to measure TWC and LWC, sensors for stagnation temperature and humidity [26].

![Airfoil schematic with dimensions in mm][26]
The ice thickness was monitored with both still and video camera located above and to the side of the test section. Camera flashes were used to synchronize the cameras. The video camera mounted above the test section was primarily used to measure ice thickness. A code was developed to find the leading edge of the ice based on a jump in intensity from the background of the test section to the ice, as seen in Figure 1-18. A mapping function was developed to determine the actual ice thickness, G, from the observed thickness, \( G_{\text{pix}} \), based on the angle of attack of the airfoil, \( \alpha \), camera angle, \( \beta \), and a scaling factor, S. The scale factor is the ratio of the length of the pixel based on the image over the actual pixel length[27].

\[
G = \frac{G_{\text{pix}}}{S \cos(\alpha + \beta)} \tag{1}
\]

Data was collected continuously throughout each test, and the ice thickness was measured at each frame, as seen in Figure 1-19. A trend line was set through the data to determine the ice accretion rate. In the sample shown, the test conditions were Mach number = 0.20, \( P = 45 \) kPa, \( \text{TAT} = 14.5 \degree \text{C} \), \( T_{\text{wb}} = -1.8 \degree \text{C} \), \( \text{IWC} = 5 \text{ g/m}^3 \), and \( \text{LWC} = 1 \text{ g/m}^3 \). The rate of ice accretion was 0.0482 mm/s[27].

Figure 1-18: Top view of iced airfoil after edge finding post processing [27]
Test were conducted at $T_{wb} = \pm 2^\circ C$ to see the effects of wet bulb temperature. It was seen that water would freeze to the airfoil without the addition of frozen particles when $T_{wb} < 0^\circ C$. When ice particles were added to the air stream, the leading edge ice thickness increased and the back of the ice shape decreased. This effect was thought to be caused by an impact-sintering mechanism for particles impacting normal to the surface and erosion by particles impacting at an angle. Large ice accretion was seen at $T_{wb} > 0^\circ C$, but a large IWC was required and the ice did not adhere well. Smaller ice accretions were seen at $T_{wb} > 0^\circ C$ and lower IWC conditions, but the effect IWC had on accretion rate was non-linear[27].

1.3.5. Inner-Compressor Duct Bleed Slot at NRC

A duct was designed to maintain constant isentropic Mach number on the forward facing surface, and the test section window was modified to match the contour of the model, as seen in Figure 1-20 (a). The slot opening size could be changed, and two colored posts in front of the slot were used as an ice thickness gauge and represented fixed compressor vanes, as seen in Figure 1-20 (b).
The first set of tests were conducted at $T_{wb} = \pm 2^\circ C$ and at various particle sizes. At $T_{wb} = +2^\circ C$, the IWC was 17 g/m$^3$ and no additional water was added to the flow. The ice that accreted above freezing was slushy and more ice accreted when then particle size was smaller. The ice shed immediately after the ice injection was turned off. At $T_{wb} = -2^\circ C$, the IWC was 4.5 g/m$^3$ and additional water was added to the flow at a LWC of 3 g/m$^3$. The same accretion pattern was seen, but the smaller particles accreted more ice[5]. The ice accreted below freezing was more solid and clear. Sample images for 4 minutes of accretion can be seen in Figure 1-21.

Figure 1-20: (a) Bleed air slot mounted in test section and (b) bleed air slot with variable openings and colored post to measure ice thickness and represent fixed vanes [5]
Figure 1-21: (a) Ice accretion for Twb = +2 °C and (b) Ice accretion for Twb = -2 °C [5]
The ice shape on the front face was traced then modeled in 3D using CAD software to determine the mass of accreted ice. The ice mass per meter of duct was calculated and the maximum was 1.2 kg/m. The potential mass of ice accretion on a typical turbofan was estimated to be 4 kg. Shed ice with such large mass could damage downstream components. The accretion rates were measured and compared to theoretical collection efficiency models. The accretions rates ranged from 0.02 mm/s to 0.35 mm/s. In both tests the injected IWC was 17.0 g/m$^3$. In the first case, the total air temperature was 7.9˚C and the wet-bulb temperature was 1.4˚C, and in the second case, the total air temperature was 7.5˚C and the wet-bulb temperature was 1.0˚C. The biggest difference in the two cases was the particle size distribution. The accretion rate increased as the ice particle distribution shifted to smaller particles rather than fewer bigger particles[5].

1.3.6. Altitude Scaling of Ice Crystal Accretion at NRC

Studies at NRC have been conducted to determine the important factors for developing altitude ice crystal scaling laws [28]. Currie et al. accreted partially melted ice particle clouds to a body with a hemispherical nose and conical after body as seen in Figure 1-22. The tested were conducted at an air speed of Mach 0.25, total pressures of 34.5 kPa and 69 kPa, wet bulb temperatures from -2°C to 6°C, and total air temperatures form 8°C to 15°C. The MVD was 45µm and the TWC was 8g/m$^3$.

![Rear window](image)

**Figure 1-22: Accretion body for scaling experiments** [28]
A pressure compensated melt potential ($\theta$) was derived relating the melt potential to the wet bulb temperature ($T_w$), far field temperature ($T_{\infty}$), liquid pressure ($p_l$), and far field pressure ($p_{\infty}$) as seen in Equation 1-2. It was seen that the ice accretion could be matched at 34.5 kPa and 69 kPa when the melt ratio was matched by TWC or melt potential. Melt ratio was used as the only dependent variable for scaling pressure. The accretion was not affected by $T_w$ at constant melt ratio, and ice accretion rate was proportional to TWC. The ice accretion was also dependent on TWC and MVD for a fixed melt ratio [28]. The experiments previously conducted showed the important factors for engine icing LWC/IWC ratio, particle size, and wet bulb temperature with the LWC/IWC being the most important. Because of this, the LWC/TWC will be the focus of the current research.

$$\theta = 1.134 \left\{ T_w + 1741 \left( \frac{p_{l,T_w-611}}{p_s} \right) \right\} - 0.134T_{\infty}$$

Equation 1-2

1.4. Engine Icing Modeling

Codes have been developed to study melting ice particle clouds and particle trajectories in engines, as well as simulate engine dynamics in icing conditions. The ice particle melt program developed by NASA Glenn balances the mass, momentum, and energy in a cloud to study the interaction between the ice, water, and air [29]. The model predicts the water to ice ratio of a cloud based on MVD, TWC, IWC, LWC, air and droplet temperatures, and humidity. This model will be covered in more detail in Chapter 4. Researchers from Pratt & Whitney conducted a Monte Carlo particle trajectory simulation to determine the particle paths, MVD, IWC, and impingement angles [30]. Both cruise and idle conditions were studied with a seed particle size of 150 µm. Ice particle break up was determined by comparing the normal impact velocity to the critical velocity.
The average particle size was calculated at every rotor location in the low pressure compressor. A schematic of the engine model can be seen in Figure 1-23.

Figure 1-23: Engine model schematic

![Engine model schematic](image)

Figure 1-24: Post impact average particle diameter [30]

![Post impact average particle diameter](image)
As seen in Figure 1-24, the average particle size was three times larger for the idling engine because the impact velocities were lower. There was a 9.5% reduction in average diameter from R2 to R3, and there was no more reduction in diameter after R3 during idle. During cruise, there was an 11% reduction in average diameter from R2 to R3, 5.7% from R3 to R4, and 2.1% from R4 to R5. The majority of the ice particle breakup happens at the fan and R2. [30]

Early engine models lacked the ability to model ice accretion in the engine. To simulate ice accretion, a compressor blockage was introduced. Blocking the compressor increased the likelihood the compressor would surge and decreased the mass flow though the engine core, causing the controller to command more fuel to the combustor to maintain the engine pressure ratio (EPR). To see the transient effect of ice accretion, a clear compressor map was transitioned to the 20% blocked compressor over 10 seconds. The output from the engine simulation can be seen in Figure 1-25. The fuel rate ($W_f$) increased to maintain the EPR. With more fuel to burn, more power was available, so the core shaft speed ($N_c$) and fan shaft speed ($N_f$) increased. With more air flowing though the bypass duct, the thrust ($F_{net}$) increased, so this early model did not represent the phenomenon correctly[31].
More complex codes have been developed that model ice accretion and engine performance together [31,32]. The code tracks particle trajectories, evaporation, and melt rate. The region of interest was the exit guide vane (EGV) tandem stators. For the cases where ice accretion was seen, the particle melt percentage was between 2% and 21% at the EGV. Tests were conducted in the NASA PSL to validate the code. The code was run for every case that ice accretion occurred and the total, static, and wet bulb temperature at the EGV along with the engine ambient temperatures were recorded. As seen in Figure 1-26, the wet bulb temperature varied little for the cases where ice accretion accrued [33].

Figure 1-25: Engine outputs for 10 second transition from clear to 20% block compressor [31]
The NASA GlennICE program was enhanced with the capabilities to model ice particle and mixed-phase icing. The particle drag equations, particle energy balance, particle and air coupling, coefficient of restitution, ice erosion, and surface energy balance were modified. The engine model was based on the NASA Energy Efficient Engine, and engine performance was modeled with the Numerical Propulsion System Simulation. It was shown that it is possible to model ice accretion on the primary air splitter at the entrance of the low pressure compressor section of an engine which could block the air from entering the compressor and cause power reduction. See Figure 1-27 (a) for splitter location schematic and Figure 1-27 (b) for ice accretion shape after 5 minutes of accretion[32].
1.5. Objectives

The goal of the research was to develop a novel facility capable of testing fundamental partially melted ice particle icing physics and to collect ice accretion data related to mixed-phase ice accretion because a mix-phase cloud is the most important factor in engine core icing that
causes power losses. To achieve this goal, the following objectives were completed during this research:

1. Design and fabricate a novel facility capable of partially melting ice particle clouds for fundamental research
2. Collect ice accretion rate data to determine icing regimes, and build a database for model validation.
3. Compare the NASA Glenn mixed phase cloud model to single particle experiments

This is the first time a facility has been designed to partly melt ice particle clouds that froze under representative conditions. This facility was also designed with operating costs in mind. It is a tool to validate future models and evaluate future mixed-phase sensors.

1.6. Dissertation Overview

Chapter 2: Icing Wind Tunnel Design and Calibration

A novel mixed-phase icing facility was designed, fabricated, and calibrated. NASA icing nozzles were used to generate an ice particle cloud, and the ice particles were melted in a hot air duct in the center of the tunnel. After exiting the duct, the mixed-phase cloud impinged on a temperature controlled plate. The MVD, LWC, and duct temperature uniformity were calibrated.

Chapter 3: Ice Accretion Results

The effects of duct temperature and plate temperature on ice accretion were studied. Regions of ice accretion, particle bounce off, and full particle melt were determined. The qualitative characteristics were also presented and two different types of ice accretion were seen.

Chapter 4: NASA Glenn Ice Particle Cloud Melt Code Validation via Single Particle Experiments
An attempt was made to correlate the NASA particle cloud melt code. Since there is no accurate method to measure the melt ratio in a partially melted particle cloud, experiments were conducted on a single particle using novel testing methods that will be described in this section. The code was manipulated to simulate a levitating single particle rather than a mixed-phase cloud.

Chapter 5: Consultations and Recommendations

The critical findings and lessons learned from this research are presented in the final chapter and recommendations to further develop the capabilities of the facility are made.
2. Icing Wind Tunnel Design and Calibration

The Penn State Icing Tunnel (PSIT) is a unique facility designed to test the engine core icing phenomenon. The PSIT can produce a mixed-phase icing cloud similar to what is seen in the compressor section of an engine. Fundamental ice accretion experiments were performed at sea level conditions to eliminate the costs associated with simulated altitude testing and to understand the initial accretion dynamics at varying icing regimes. Air assisted atomizing nozzles generated a cloud of water droplets that froze due to the pressure drop from 75 psi to 14.7psi at the nozzle exit and convection as they flowed through the tunnel. The ice particle cloud in the center of the tunnel flowed through a duct where hot air was introduced. The hot air melted the particles to a desired percent melt. At the exit of the duct, there was a temperature controlled flat plate for the mixed-phase cloud to accrete to. Videos of the ice accretion process were recorded to study impingement characteristics (instantaneous freezing, splashing, flowing), and photos of the ice accretion were taken post-test to measure ice thickness and surface characteristics. The details of the PSIT design and construction will be presented in this chapter.

2.1. Tunnel Core Components

The tunnel is laid out in a modified vertical closed circuit design partially enclosed in a freezer. The tunnel is 4.9m tall, 6.7m wide, and is powered by an 88kW three phase electric motor. As seen in Figure 2-1, the bottom part of the tunnel is connected through the freezer, but the top section is open to the freezer to exchange air between the tunnel and freezer. The freezer is required because the evaporators needed to cool the tunnel are too large to fit within the cross section of the tunnel, so they are hung in the freezer. The freezer is 2.4m wide, 3.0m deep, and 4.9m tall. The tunnel flow blows across the primary ten ton evaporator, and the auxiliary evaporators are used for initial facility cooling. The spray system and test section were placed in the sections of the tunnel...
depicted in Figure 2-1 to maximize the cloud cooling time. The turning vanes between the test section and the spray system further discriminated between ice particles and supercooled water droplets. Any droplets that were not fully glaciated accreted to the bottom right turning vanes prior to entering the test section region, ensuring that only 100% glaciated particles reached the test sample. The small amount of ice accreted to the turning vanes during the test was removed post-test using surface heaters. The test section is 0.62m tall, 0.93m deep and has a top speed of 35m/s. The tunnel temperature can be controlled from room temperature to -20.0°C, but heats up at a rate of 1.0 °C/min so test times were limited to 2.5 minutes.

![Figure 2-1. PSIT front and side layout schematic.](image)

### 2.2. Cloud Generation

The cloud was generated with air assisted atomizing nozzles. The nozzles were NASA Standard icing nozzles [34–36]. Water was supplied to a 0.635mm needle and air was supplied to the cavity between the needle and needle housing as seen in Figure 2-2 (a). The air cuts across the water stream to atomize the water. Four nozzles were used, and the nozzles and supply hoses were contained in a fairing, as seen in Figure 2-2 (b). To protect against freezing water, the fairing was insulated and the nozzle housings were heated.
Figure 2-2. (a) NASA standard icing nozzle in housing (b) nozzle fairing schematic

The droplet size distribution is governed by the difference between the water and air pressure. The water droplet particle size increases with the pressure differential between water and air since the shearing effect of the water relative to the water velocity decreases. The Median Volumetric Diameter (MVD) for the nozzles used was calibrated by NASA for varying input pressures. The MVD for different air pressures inputs was correlated to the pressure differential between the water pressure and the air pressure to the nozzle. Polynomial fittings of the results (see Figure 2-3) were provided by NASA, allowing for the quantification of water droplet particle sizes based on input pressures. In the equation provided by NASA, the dependent variable, air pressure ($x$), is in units of pounds per square inch, psi, and the second dependent variable, the delta pressure between water and air ($y$), is also provided in psi. The details of the MVD calculation can be seen in Equation 2-1 and the coefficients are listed in Table 2-1. The MVD coefficients were determined experimentally by NASA [34].

$$MVD = a + bx^c + dy^e + fxy^e$$  \hspace{1cm} \text{Equation 2-1}
Table 2-1. MVD coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Standard nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>14.3</td>
</tr>
<tr>
<td>b</td>
<td>-656</td>
</tr>
<tr>
<td>c</td>
<td>-1.98</td>
</tr>
<tr>
<td>d</td>
<td>-0.00237</td>
</tr>
<tr>
<td>e</td>
<td>1.42</td>
</tr>
<tr>
<td>f</td>
<td>88.5</td>
</tr>
</tbody>
</table>

Figure 2-3. NASA Standard icing nozzle calibration curves [34]

In practice, the MVD is controlled by commanding air pressure and MVD, and a feedback control system controls the required water pressure. Figure 2-3 is a graph of MVD vs delta pressure with air pressure isobars. Since a large pressure drop from the nozzle to atmospheric pressure is required to generate particles, the maximum available air pressure of 45 psi (310kPa) was supplied to the nozzles, and the water pressure was 75psi.
2.3. Hot Air Generation and Distribution

Hot air was required to melt the ice particles to a desired percent melt. It was not practical to heat a large section of the tunnel due to power limitations, so a small region down the center line of the tunnel was heated. Three (3) 18kW three phase electric heaters were used to heat the air supply. The exit temperature limit of the heaters used set by the manufacturer was 760°C, but the heaters were limited to 500°C during testing. During testing, the duct temperature ranged from 3.5 to 24.0 °C. As seen in Figure 2-4 (a), three heaters were run in parallel. A selector valve placed after the heaters vented the air out of the tunnel when duct heating was unwanted. The hot air was introduced to the tunnel though a distribution ring, seen in Figure 2-4 (b), to maximize thermal uniformity. The hot air was supplied to the top and bottom of the reservoir, and the air flowed through eight 0.25 inch (0.64cm) holes evenly spaced around the ring and set at 30°. A PID control system was used to maintain the heater temperature such that the temperature of the heating section remained constant at a pre-selected temperature. A thermocouple in the distribution ring was the used by the controller to maintain the desired duct temperature. A thermocouple in the duct was used to set the ring temperature before cloud generation but was not reliable once the cloud was turned on due to ice accretion. For this reason, the correlated temperatures between the duct temperature and the ring temperature were used to determine the temperature in the duct during testing, based on the temperature of the ring. This system does not account for the potential of evaporative cooling form the cloud.
A pitot static probe was used to measure the air speed at the exit of each hot air injection port in the hot ring. As seen in Figure 2-5, the port exit velocity was uniform. The average speed was 56 m/s with a 5% standard deviation. Port numbers 1 and 5 had the highest velocities because those ports were in line with the hot air supply pipes.
2.4. Hot Duct Design

A duct was required downstream of the distribution ring to concentrate the hot air in the center of the tunnel. Without a duct, the hot air would have mixed with the cold tunnel air, and the heating capability of the system would be negligible. Two duct configurations, seen in Figure 2-6, were evaluated to maximize temperature and velocity profiles. Option one was a duct with the same diameter as the inside of the distribution ring. The rationale behind option 1 was to concentrate the hot air provided by the distribution ring, and to minimize any potential wake that could slow the air at the test region (located 6.0cm from the exit of the hot duct). A potential hazard from option 1 was water particles could impact the hot walls of the duct, fully melt, and travel as water to impact the accretion plate, contaminating the results. Duct option 2 was conceived to eliminate the runback problem. The duct conceived for option 2 had a diameter larger than the outside of the distribution ring and also much larger than the flat plate impacting surface. Cold air would bypass the distribution ring and keep the duct wall cold, so ice particles could not melt when impacting the walls. Any minimal water created against the walls and traveling down the tube would not impact the flat plate, since the tube diameter would exceed the size of the plate. The problem with option 2 was the wake from the ring would reduce the velocity in the test region.
Computational Fluid Dynamics commercial software was used to evaluate the temperature and velocity profiles in the two ducts configurations. A Reynolds-averaged Navier-Stokes with a k-ε turbulence model was used with a structured mesh, and 2% turbulence. The tunnel conditions modeled were -10°C and 30m/s or 60m/s depending on the case. The temperature field was first compared at a tunnel speed of 30m/s. As seen in Figure 2-7, the hot air in the first duct design stayed close to the duct wall and did not diffuse to the center until the end of the duct. As expected, the cold bypass air for the second duct shielded the duct wall from the hot air, and the hot air diffused to the center of the duct faster.
The center line temperature distribution was compared between both models to see which duct flow had more air above 0°C. As seen in Figure 2-8, the models predict only the end of duct one to reach above freezing temperatures, and the entire length of duct two was above freezing. Neglecting the velocity fields, duct two presented a better option to partially melt incoming ice particles for a given available input power.

Figure 2-8. Center line air temperature of duct for 30m/s tunnel speed
The velocity in the region of the accretion plate was also a critical parameter to evaluate. As seen in Figure 2-9, there was only a 3 m/s velocity deficit at the exit of duct one in the region of the impact plate (denoted by the dashed square), but the wake of the heat distribution ring reduced the velocity at the duct exit to half of the free streams for duct two. The scale for Figure 2-9 goes from 0 to 30m/s. The scale in future figures is different.

Figure 2-9. Duct velocity field for test section speed of 30m/s

For a more even comparison, the second duct was run at twice the tunnel speed to match the velocity at the accretion plate. Notice in Figure 2-10 the scale changed to 0 to 60m/s. The velocity field for duct one is the same because the tunnel speed remained the same. The tunnel speed for the second duct was doubled to 60m/s to have a velocity of 30m/s in the region of the accretion plate.
The final temperature field comparison can be seen in Figure 2-11. Duct one was run at 30m/s tunnel speed, and duct two was run at 60m/s tunnel speed to match accretion plate region speeds. In this final case, duct one had the same temperature field as it had before, but duct two had a degraded temperature performance at its exit. There was not enough hot air available to heat the core of the duct at 60 m/sec flow velocities. For this reason duct one was chosen for fabrication.

The duct and distribution ring were insulated before being installed in the tunnel. As seen in Figure 2-12, the duct was hung in the center of the tunnel with the exit of the duct 0.06m in front of the
accretion plate. Three 3/8” threaded rods were used to rigidly suspend the duct from the top of the tunnel.

![Figure 2-12. Duct installation schematic](image)

2.5. Humidity Sensing Attempt One – Relative Humidity Sensors

Capacitance based relative humidity (RH) and temperature sensors were first installed in the hot duct to quantify the environmental conditions due to the low cost and small size of the sensors. Each RH sensor was paired with a temperature sensor so specific humidity could be calculated. The first RH and thermistor pair was placed on the exterior of the spray system fairing on the side opposite to the cooling system to protect them from any stray recirculating cloud. The RH would read 100% if the cloud came in contact with the RH sensors, because water would impinge directly in the sensor. To eliminate this problem, the sensors were placed outside of the duct and a vacuum system pulled air from the duct to the sensors. As seen in Figure 2-13, there were four inlet locations, three in the duct and one up stream, to measure initial conditions. The inlets faced down steam to minimize ingestion of the cloud, and the inlets in the duct were spaced radially, so the downstream inlets were in clean flow.
Figure 2-13. RH and temperature sensor inlet placement

The air was pulled from the tunnel and went through a cyclone separator and passed a nylon filter before flowing over the sensors. A diagram of the vacuum and filter system can be seen in Figure 2-14. Each sensor pair had a dedicated filtration system to remove any cloud that was ingested at the inlet. The filtration system made it possible for the sensors to measure the conditions in the air in the cloud without getting contaminated from the droplets in the cloud.
In practice, the RH sensors were not effective. It was not possible to keep the sensors free of condensation and frosting. The sensors read between 90% and 100% regardless of the tunnel conditions once the tunnel temperature was below freezing. This system was dismantled and replaced with a robust gas analyzer as discussed in section 2.6.

2.6. Humidity Sensing Final Solution – Gas Analyzer

A LI-COR LI-840A gas analyzer was selected to replace the RH sensors. Due to the cost of the system, only one was acquired, so measurements were taken at the exit of the duct. The analyzer used a non-dispersive infrared gas analyzer based of a single path and dual wavelength detection system. It measured H$_2$O from 0-60 mmol/mol and CO$_2$ from 0-20000 ppm. As seen in Figure 2-15, air was drawn into the optics via an external pump and flowed through the optical path. The water and carbon dioxide absorb different wavelengths of IR light (2.595 µm for water and 4.26 µm for CO$_2$). The concentrations are determined by the ratio of the initial IR intensity to the intensity after absorption. The broad band IR light was filtered for each measurement prior to entering the detectors. The incoming air from the duct exit was filtered continuously with a 1µm filter before entering the analyzer [37].
2.7. Accretion Plate Design

A flat plate was chosen as the accretion surface over a more representative airfoil shape for three reasons. The most important reason for selecting a flat plate was surface temperature controllability. The accretion surface was placed in the hot exhaust of the duct, so it had to be cooled. A Peltier semiconductor (thermopile) was used in conjunction with a liquid cooling system to maintain the desired surface temperature. A PID controller was used to maintain the surface temperature. A Peltier uses the thermoelectric effect to generate a temperature difference proportional to the voltage input. As seen in Figure 2-16(a), two 4.8 cm by 2.4 cm semiconductors were used together to make one 4.8 cm square. The semiconductors were placed behind a 1.2 mm thick aluminum accretion surface. The heatsink that removed the heat from the back of the Peltier was a 5.6 cm square. Coolant was pumped from the heatsink to the heat exchanger which was placed inside a secondary freezer. The coolant temperature was kept below freezing to reduce the power required for the Peltier to maintain a desired temperature. A thermistor on the surface of the plate was used to record the surface temperature and for the Peltier feedback control system. The
feedback configuration used a pulse modulated wave (PWM) to control surface temperature. As seen in Figure 2-16(b), the plate is rigidly suspended from the top and bottom of the tunnel by a pair of threaded rods, so the angle of attack of the flat plate could be varied.

![Figure 2-16. (a) Accretion plate schematic (b) Accretion plate installed in tunnel](image)

2.8. Cloud MVD Calibration

The particle size distribution generated by the nozzles was dependent on the Δp between water and air pressures provided to the nozzles (calibrated by NASA as discussed in Section 2.2). The distribution at the test section was verified because of potential negative effects related to the cloud interaction with the turning vanes. A Phase Doppler Interferometer (PDI) was used to measure the ice particle sizes. The PDI was a flight probe manufactured by Artium designed to fly through clouds. As seen in Figure 2-17, the PDI was installed just before the entrance of the duct.
A single laser in the PDI was split into four beams, two for each set of optics. In this test, only one optical range was used. As seen in Figure 2-18, the two coherent laser beams intersected at one point in space where they measure particle sizes of traveling droplets. When a droplet entered that region, the beams were distorted by the droplet and created a phase shift between the two light waves. This made an interference pattern on the sensor and the particle size and velocity was determined from the interference pattern [38].

Data was taken for 5 seconds in three different clouds. The particle diameter distributions can be seen in Figure 2-19, and the cumulative volume fraction can be seen in Figure 2-20. In all three cases, the requested MVD was 23µm. The MVDs experimentally measured for the three
cases were 25µm, 24µm, and 23µm. In every case, the distribution was skewed towards smaller particles. The particle count fell off faster for the smaller particles than the large ones. A few particles several times larger than the median were also measured, but their counts were not consistent in each test. These results verify that the cloud generation was working properly and that the turning vanes did not affect the cloud.

Figure 2-19. Cloud particle diameter distributions

Figure 2-20. Cloud particle cumulative volume fraction
2.9. Cloud TWC Calibration

The total water content (TWC) of the cloud was one of the most important variables need to be quantified to determine ice accretion rates. The more water there was in the cloud, the faster the ice would accrete. SEA Inc. developed a hot wire based TWC/LWC sensor that could take data continuously during testing. NASA used this probe during wind tunnel testing at NRC, and this sensor had cross talk between channels and did not account for 50% of the IWC [23]. Since a sensor was not available, two other methods were used to determine the TWC in the PSIT. For the first method, the TWC was calculated from the water flow rates of the nozzles, tunnel geometry, and airspeed. The volume flow rates ($\dot{W}$) for the nozzles were measured by NASA for varying input pressures to the nozzle. The flow rate of the nozzle was related to a flow coefficient ($C_F = 0.012$) times the square root of the water-air pressure differential, $\Delta P$, as seen in Equation 2-2. The volume flow rate, in gal/min, was converted to a mass flow rate ($\dot{M}$) in g/s, as seen in Equation 2-3. Then the TWC was calculated by multiplying the mass flow rate of one nozzle by the number of nozzles ($\delta$), and dividing by the local tunnel area ($A$) and speed ($V$) seen in Equation 2-4. This method yielded a TWC of 1.7 g/m$^3$ [35] for the nozzle conditions selected (45 psi air pressure, 23 MVD, 4 nozzles).

\[
\dot{W} = C_F \sqrt{\Delta P} \quad \text{Equation 2-2}
\]
\[
\dot{M} = \dot{W} \frac{3785}{60} \quad \text{Equation 2-3}
\]
\[
TWC = \frac{\dot{M} \delta}{AV} \quad \text{Equation 2-4}
\]

The second method to measure TWC was to directly collect the ice at the duct exit and weigh it. The TWC was then calculated from the ice mass, icing time, duct geometry, and local velocity. A 0.48 m nylon filter was attached to the end of the duct, and a heated pitot static probe
was placed in the middle of the filter. A photograph of the setup can be seen in Figure 2-21 (a), and a sample of collected ice can be seen in Figure 2-21 (b). The tests were conducted at a nominal tunnel temperature of -15°C but ranged from -17°C to -13°C. The initial air speed at the duct exit was 20 m/s. After each test the filter with the ice was weighed, and the dry filter weight was subtracted to determine ice mass.

Five samples were collected for an icing time of 2.5 minutes with a 1s (0.7%) standard deviation. The average ice mass collected was 52.4g and had a standard deviation of 4.4g (8.4%). The duct entrance velocity was calculated to be 23.6 m/s using the area ratio of the tunnel. The duct entrance area used in the TWC calculation was 0.0095m². The TWC calculated for the entrance of the duct was 1.5 g/m³ with a standard deviation of 0.2 g/m³ (11.1%). The TWC at the entrance of the hot duct was 12% lower than the calculated TWC from the flow rates, as discussed above. The two methods to measure TWC at the entry of the hot duct provided results within the standard deviation of the tests, validating both methodologies. The TWC at the duct exit was not the same as at the inlet due to changes in velocity and geometry along the hot duct. The duct exit is 60% smaller than its entry because the fairing on the distribution ring acts like a funnel, and the
initial velocity was 15% slower. Using the initial velocity and exit area, the TWC at the exit was calculated to be 4.4 g/m$^3$ with a standard deviation of 0.5 g/m$^3$ (11.1%). One problem with this setup was the filter clogs over time, so the final velocity of the test was slower than the initial, as seen in Figure 2-22. In the 2.5 minute cases, the velocity dropped to 10.4 m/s with a standard deviation of 0.9 m/s (8.6%). During ice accretion testing without the use of the filter, the velocity would not change. For this reason, the initial velocity was chosen to calculate TWC from the collected ice mass. However, the reduction in velocity raised question about the validity of the 2.5 minute-collection results.

![Figure 2-22. Sample time history of exit velocity during 2.5min TWC ice collection](image)

More ice was collected at a much shorter icing time to remove the velocity degradation potential effects and to verify the initial results. Three cases were collected at an icing time of 13.7s with a standard deviation of 1.2s (8.4%). As seen in Figure 2-23, the duct exit velocity was constant throughout the test. The average ice mass collected for the three cases was 5.2 g with 1.6g (31.0%) standard deviation. The higher deviation was attributed to the difficulty in controlling the shorter icing time accurately, since instantaneous shut down of the cloud was not possible.
This data yielded an entrance TWC of 1.7 g/m³ with a standard deviation of 0.4 g/m³ (24.9%), and an exit TWC of 4.9 g/m³ with a standard deviation of 1.2 g/m³ (24.9%). The TWC calculated from the 13s cases agreed with the flow rate method and the 2.5 minute ice exposure time cases when the velocity reduction was ignored, as seen in Figure 2-24. The second set of data validates the approaches taken to quantify TWC.

Figure 2-23. Sample time history of exit velocity during 13s TWC ice collection

Figure 2-24. Summary for TWC for different calculation methodologies
2.10. Duct Temperature Profile Uniformity

The duct temperature distribution was measured experimentally with a thermistor rake. As seen in Figure 2-25, the rake was in a cross shape that fit to the inner diameter of the duct. There were two thermistors on each arm and one in the middle, making nine total thermistors. The inner ring thermistor radius was 1.3cm (0.5inch) and the outer ring was 2.5 cm (1.0inch). Data was collected at six locations spaced 0.3m apart down the duct. The tests were conducted at a tunnel temperature of -15°C and a duct set point of 10°C.

![Thermistor rake diagram](image)

Figure 2-25. Thermistor rake diagram

A time history for the data taken at 61 cm downstream of the hot air injection ports can be seen in Figure 2-26. The heaters were turned on at time zero. The heat in the duct increased at 0.75 °C/s for 20s. Then, the rate dropped to 0.1 °C/s because the heater temperature was hitting the 500°C maximum temperature limit. The controller was cutting the power until the heater temperature reduced to below the limit, then power was restored. This on/off power cycling was the cause of the temperature oscillations from 20s to 140s. At 140s the duct temperature neared the set point and the PID controller reduced power and maintained 10°C in the duct as desired. At 350s the heater power was cut and the hot air was diverted out of the tunnel while the heaters cooled.
The outer and inner ring temperatures were averaged at each position and compared down the length of the duct. As seen in Figure 2-27, the duct temperature was uniform down the length once the hot air penetrated to the center of the duct, and the center of the duct was 3°C higher than at outer ring. The experimental temperature distribution was more uniform than the prediction discussed in Section 2.4.
3. Ice Accretion Regions Results

The data collected for this research was taken to determine what combinations of surface temperature and particle percent melt enhanced ice accretion. The goal was to identify the regions of strong ice accretion, water runoff, and particle bounce off. The ice accretion plate used during testing and the temperatures of a heating duct used to partially melt ice particles were varied over the range of the facility capabilities. The temperature of the plate, heating duct, humidity at the end of the duct, and footage of ice accretion were acquired for all tests. If ice accreted to the impact plate during the test, photographs of the ice were taken to determine its thickness. The details of the ice accretion results will be presented in this chapter.

3.1. Test Matrix

The test matrix was defined by the heating duct used to partially melt incoming ice particles as well as the plate surface temperature selected during testing. The plate surface temperature ranged from -6.0 °C to 6.0°C, and the heating duct was controlled between -5.0°C and 30°C. The range of temperatures to be tested were selected prior to the construction and calibration of the tunnel. The final capabilities of the facility limited the test matrix controllability. The original plan was to increment the plate temperature by 2.0°C and the duct by 5.0°C. This made a matrix of 55 cases, as seen in Table 3-1. In practice, it was difficult to exactly match these cases due to the controllability of the temperatures, especially in the high temperature region of the matrix. Test cases were named based on what condition they most closely matched. Repeat cases were noted with ascending letters (Case##a, Case##b, Case##c, etc.)
Table 3-1. Test matrix with case numbers

<table>
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<th>Plate Temperature °C</th>
<th>-6</th>
<th>-4</th>
<th>-2</th>
<th>0</th>
<th>2</th>
<th>4</th>
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<td>25</td>
<td>33</td>
<td>41</td>
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<td></td>
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<td>10</td>
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</tr>
<tr>
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<td>16</td>
<td>24</td>
<td>32</td>
<td>40</td>
<td>48</td>
</tr>
</tbody>
</table>

3.2. Testing Procedure

The mix-phase icing facility consumes a huge amount of laboratory resources and required at least two people to run a test. The testing procedures are described below:

Initialize tunnel

Start both LabVIEW codes

Zero nozzle pressure sensors

Turn air and by pass on so nozzles do not freeze

Turn on both cooling systems to full blast (under -20°C)

Tunnel should be -19 °C or colder be for starting test to give time to adjust heater temperatures

Prepare heaters

Open air supply valve

Send air to duct via LabView

Turn on controlling units

Set temperatures to below current temperature
Turn main power on

Increase temperature 2°C at a time to slowly warm heaters to burn off condensation at low power

Once heater internal temperature is above 100 °C, set temperature to desired level

Start SH sensor

Turn on sensor and pump

Match sensor scale to LabView

Lights & Camera

Send hot air to camera

Turn on lights (HMI takes 2 minutes to warm up)

Start live view in Nikon Camera Control

Change to video record mode

If record time is less than 10 minutes, format card

Set aperture to maximum ( f/32 for 60mm macro)

Frame rate fixed at 60Hz

Set appropriate ISO (approximately 460)

Set up Peltier

Set desired temperature

Verify correct thermistor (15k)

Verify controller mode (PDI start point P = 10, I = 5, and D = 1)

Verify power mode is not reversed and hot/cold gains are 1

Turn on Peltier after heaters are ready so the coolant does not heat

Run test
Start tunnel once heaters reach the set temperature and increase speed 100 RPM at a time
When fan reaches 700 RPM, pull hoses from pitot probe transducer and zero transducer
Input ambient pressure
Adjust RPM to reach 20 m/s
Adjust heaters as needed, understanding tunnel will have to warm up from -19 to -13 °C
Start saving data and record video once heaters are set and tunnel temperature is between -12 and -13°C
Record 10s to 30s of data then start cloud
Press “Cloud On” when cloud appears in tunnel
Turn off cloud after 145s (cloud will take ~5s to dissipate)
Leave vacuum on until pictures are completed
Press “Cloud On” when cloud disappears in tunnel
Switch hot air from the duct to exhaust
Drop Peltier temperature to below freezing if it is not already, so the ice does not melt
Stop tunnel and return RPM to 35
Shut down heaters
Take pictures
Take pictures of ice accretion (or no accretion) with wide angle lens
Melt ice on the left half of the plate with a hot plate to expose the ice thickness down the center
Take pictures of ice accretion with wide angle lens
Place ruler in tunnel and in plane of the ice edge
Fix camera and 200mm macro lens to tripod
Verify laser is centered
Line up plate and camera so half the laser hits the side of the plate and the other half only highlights protrusions from the plate surface and does not shine directly on the surface.

Turn on LEDs
Set camera settings so the ice stands out and the plate is dark (starting point - aperture: f/32,
ISO: 800, shutter speed: 1/40; change shutter speed and ISO as needed, not aperture)
Take three pictures from top to bottom with overlap

Clean & Reset
Purge cloud
Defrost for 20 minutes
Brush off evaporator filter
Turn on turning vane heaters and clean turning vanes
Run tunnel at 900 RPM to clean debris
Cool back down

3.3. Data Reduction

3.3.1. Ice Thickness Measurements

Ice thickness was collected for every test with ice accretion. Measurements with mechanical devices were not practical because the ice thickness was thin (< 2 mm) and not always uniform. Photographs were taken of the ice profile down the center of the plate and the ice thickness was quantified from the digitized images. As seen in Figure 3-1, half of the ice was melted using a heated plate to expose the center line profile.
A 200mm macro lens was used to capture the side profile images of the ice. The field of view of the lens was set to maximize the amount of detail captured in the image, but the entire plate was not able to fit into the field of view. Three images were taken of the ice profile and later stitched together into one composite, as seen in Figure 3-2. The panorama maker in Photoshop was used to stitch the images together. The rearranged images were obtained using an available algorithm within the software known as “rearrange” (not the cylindrical mapping algorithm). This algorithm was used because the camera was translated between images and not rotated. The “rearrange” algorithm did not distort the images like the cylindrical mapping algorithm would have.
The program used to measure the ice thickness required an image with an outline, a scale, and an origin. Photoshop was used to create the ice outline image. A blank layer was added above the original image. The scale and outline were painted on the blank layer, so a binary image of the ice outline and scale could be exported. First, the pixels were scaled based on the ruler. All of the images were close to 1460 pixels/cm. A 0.25 cm (365 pixel) square was painted in the corner of the plate. This marked the origin and served as a scale. The quick select tool was used to accurately select the ice area. A path was generated from the selection and the path was traced out by the brush tool on the blank layer to create the ice outline. Finally, a black and white image of the trace and scale was exported. GetData Graph Digitizer was used to digitize the outline. The square was used to set the scale and the “digitize area” tool was used to digitize the outline. Points were generated every .05 cm down the length of the ice. A schematic representation of the process can be seen in Figure 3-3.

![Figure 3-3.Digitizing process for case 38b](image-url)
3.3.2. *Humidity & Wet Bulb*

The LI-COR gas analyzer provided specific humidity (SH) in H₂O concentration mmol(H₂O)/mol(wet air) or parts per thousand (PPT). From this data, specific humidity in g(H₂O)/kg(wet air), relative humidity (RH) in percent, and wet bulb temperature (Tₜₜ) in °C were calculated. The mixing ratio (MR) in g(H₂O)/g(dry air) was calculated by dividing water concentration by one minus the water concentration multiplying by the molecular weight of water and dividing by the molecular weight of air 18.015 g/mol and 28.97 g/mol respectively, as seen in Equation 3-1. The SH in g(H₂O)/kg(air) was calculated dividing the MR by the MR plus one and multiplying by 1000 to get the units of interest, as seen in Equation 3-2. The calculation of RH was a multi-step process involving the calculation of vapor pressures. The MR can also be determined from the vapor pressure (VP) in hPa and static pressure (Pₛ) in hPa, as seen in Equation 3-3[39]. Equation 3-3 was rearranged to have VP a function of MR and Pₛ, as seen in Equation 3-4. Next, the saturated vapor pressure (SVP) in hPa was calculated from equation developed by Bolton [40], as seen in Equation 3-5. Final RH was calculated by the ratio of VP to SVP, as seen in Equation 3-6.

\[
MR = \frac{\text{ppt}}{1000} \left( \frac{18.015}{28.97} \right) 
\]

\[
SH = 1000 \frac{MR}{MR + 1} 
\]

\[
MR = 0.622 \frac{VP}{Pₛ - VP} 
\]

\[
VP = \frac{500 \times MR \times Pₛ}{500MR + 311} 
\]

\[
SVP = 6.112e^{\frac{17.67T}{T + 243.5}} 
\]
\[ RH = 100 \frac{VP}{SVP} \]  

Equation 3-6

Wet bulb temperature \((T_w)\) was also calculated with a guess and check scheme. An initial guess was required to converge to a wet bulb temperature solution for the environmental conditions measured. The estimated saturated vapor pressure \((SVP_e)\) was calculated by guessing an initial \(T_w\), as seen in Equation 3-7. Then the estimated vapor pressure \((VP_e)\) was calculated based on the \(SVP_e, T, \) and \(T_w\), as seen in Equation 3-8 [41]. Last, the error between the \(VP\) and \(VP_e\) was calculated, as seen in Equation 3-9. The guessed \(T_w\) was adjusted until the error was less than 0.5%.

\[ SVP_e = 6.112e^{\frac{17.67T_w}{T_w+243.5}} \]  

Equation 3-7

\[ VP_e = SVP_e - 0.00066P(T - T_w)(1 + (0.00115T_w)) \]  

Equation 3-8

\[ \text{error} = \frac{VP - VP_e}{VP} \]  

Equation 3-9

Other researchers have derived the wet bulb temperature on an adiabatic surface where convective heat is balanced by the evaporative heat, and there is no heat transfer through the plate. Their conclusion was that if the wet bulb temperature was less than zero, the mixed phase accumulation was losing heat to the air, promoting freezing [26]. This was not the case in this research since the Peltier could add or remove heat to maintain the surface temperature.

3.3.3. Duct Temperature Calculation

The temperature sensor in the duct was not reliable while the cloud was on. The sensor read 0°C because the impinging cloud would freeze, insulating the thermocouple and providing a temperature reading of 0°C (Figure 3-4). The duct temperature during icing was inferred from the
tunnel free stream temperature and the difference between the duct and tunnel temperatures before
the cloud was turned on. For example, from case 12b there was a 19°C difference between the duct
and free stream before the cloud was turned on. Experiments showed a linear relationship between
the duct and free stream temperature, so the estimated duct temperature was calculated by adding
19°C to the free stream temperature after the cloud was turned on. The average of the simulated
duct temperature during the icing event was used to compare cases. This assumes the cloud has no
effect on the duct temperature. However, evaporation of the cloud could cool the air, and this is
not taken into account in the presented calculation.

![Graph showing time history for case 12b simulated duct temperature.](image)

**Figure 3-4.** Time history for case 12b simulated duct temperature.

### 3.4. Mix-Phase Ice Accretion Trends

#### 3.4.1. Ice Accretion Region Boundaries

A total of 48 tests were performed to determine the boundaries of ice accretion. The surface
temperature ranged from -4.5°C to 7.0°C, and the duct air temperature ranged from 3.5°C to 24°C.
The upper duct temperature was limited by the available power and air mass flow supplied to the
heaters. The lowest surface temperature was bounded by the Peltier maximum power. The power required to achieve a certain surface temperature increased as the duct temperature rose, so the minimum surface temperature rose with the duct temperature. Three distinct outcomes were observed: ice accretion, no ice accretion due to particle bounce off, and no ice accretion due to water runoff. All of the cases are plotted in Figure 3-5 and are colored by classification.

![Figure 3-5. Summary plot of test cases by outcome classification](image)

It was hypothesized that the ice particles would bounce off a cold surface because there was insufficient heat or water to promote ice accretion. This hypothesis was verified for duct temperatures colder than 7°C and plate temperature at or below freezing. For those cases, it was seen that no ice accreted to the plate. There was only a light layer of frost from the particles that hooked onto the surface roughness. These particles were not adhered and could be easily removed with minimal cross-flow. These cases also verified that the facility was creating fully particleized droplets.
It was also hypothesized that ice cannot persist on a surface with a temperature greater than freezing. This was demonstrated to not be true. The boundary between ice accretion and water runoff started at a surface temperature of 0 °C for a duct temperature of 5.5 °C but rose linearly to 3.0°C surface temperature at a duct temperature of 24.0°C. Even though the air and surface temperatures were above freezing, the incoming particles provided sufficient cooling to promote ice accretion. The ice accretion cases with a plate temperature above freezing highlighted the importance of the cooling capacity of the ice particles. All of the ice that accreted was solid and well adhered. The qualitative characteristics of the ice changed with duct temperature. At lower duct temperatures, the ice was opaque with noticeable surface roughness. The roughness and white ice came from the high ice particle content. There was less water at lower duct temperature, so the reduced amount of water available freezes, instantly trapping the ice particles. The ice became more translucent and smooth as the duct temperature increased. There was more water content as the duct warmed up, so more of the ice accretion came from frozen water than trapped particles. The last region observed was the water runback region. The surface temperature was high enough to melt all of the incoming ice. It was more difficult to maintain the surface temperature constant during the cases where the plate temperature was above freezing. The surface temperature dropped a few degrees when the cloud initially impacted the plate. The Peltier would typically recover to the set point within 20 seconds. The temperature reduction caused the plate surface to dip into the ice accretion region initially. Then, the ice melted when the surface temperature recovered and no ice accreted for the remainder of the test. Cases that were away from the boundary edge, such as 52a, did not see that effect, since the Peltier temperature was maintained away from the ice accretion region during the entire test.
3.4.2. Ice Accretion Rates Measurement

Ice thickness measurements were taken at the end of each test. The accretion rate was calculated from the average ice thickness at the plate center from 2.0 cm to 5.0 cm and dividing by the total icing time. Accretion rate is presented instead of total ice thickness because the exact icing time could vary up to 10 seconds due to the water clearing from the spray system lines. Ice accretion rate was selected as the comparison metric (instead of ice thickness) due to the small variability in icing time during testing. The ice accretion rate data was plotted in Figure 3-6 where each square is an individual case colorized by accretion rate. There was little correlation between accretion rate and surface or duct temperature. Case 12a had the maximum accretion rate of 1.5 mm/min, and case 28h had the minimum of 0.2 mm/min. The average rate for all the cases with accretion was 0.8 mm/min with a standard deviation of 39%. Lack of accretion rate trend was attributed to low collection efficiency. The cloud particles will follow the flow and not impact the plate. The Stokes number (Stk) characterizes the behavior for particle in a flow. If the Stk is much less than 1, then the particles will follow the flow. As seen in Equation 3-10, the Stk was calculated by multiplying the relaxation time ($t_0$) by the velocity ($V$) and dividing by the particle diameter ($D$). The relaxation time is the time constant for the exponential decay of the particle velocity due to drag. Is was calculated by multiplying the particle density ($\rho_p$), by the particle diameter ($D$), and dividing by the dynamic viscosity of the gas ($\mu_g$). The relaxation time for a 20 $\mu$m particle in air was $1.128 \times 10^{-9}$, so the Stk for a 20 $\mu$m particle at 20 m/s was 0.0011. The Stk for the particles in the cloud were much less than 1.0, so the particles followed the stream lines, reducing the probability the particle would impact against the plate explaining the difficulty of acquiring and interpreting ice accretion rates.
\[ Stk = \frac{t_0 V}{D} \]  

Equation 3-10

\[ t_0 = \frac{\rho_p D^2}{18\mu_g} \]  

Equation 3-11

Figure 3-6. Summary plot of accretion rate vs duct temperature and plate temperature

The pressure compensated melt potential was calculated for the cases with humidity data because melt potential is used for altitude scaling as discussed earlier. As seen in Figure 3-7, there was no correlation between melt potential and accretion rate.
3.4.3. Humidity and Wet Bulb Calculations

Specific humidity data using the robust gas analyzer sensor was collected for a subset of cases that represented most of the duct temperatures tested. Relative humidity and wet bulb temperatures were calculated for those cases. SH was constant with duct temperature as seen in Figure 3-8. For all the cases, the average SH was 1.12 g/kg with a standard deviation of 5%. This independence between SH and duct temperature implied that there was no evaporation of melted water as the cloud traveled in the hot duct. If the water was evaporating, the SH should have increased with duct temperature. There was no time for the water to evaporate during the test. The total amount of time the cloud spent in the duct was 0.07 seconds.
The wet bulb temperature was dependent on the duct temperature. The saturation vapor pressure increases with temperature, so the wet bulb temperature also increases. A linear relationship was seen when wet bulb temperature was plotted vs duct temperature, as shown in Figure 3-9. The wet bulb temperature was above freezing even though solid ice accreted to the plate. This would be unexpected for an adiabatic surface because the accumulation would be gaining heat from the air.
For this research the Peltier could remove heat from the accumulation, so ice could accrete at wet bulb temperatures above freezing. It was seen that ice would not accrete above a duct temperature of 15°C without the cooling capacity of the Peltier, as seen in Figure 3-10.

Figure 3-9. Average wet bulb temperature vs duct temperature

Figure 3-10. Ice Accretion rate vs duct temperature without Peltier control.
3.4.4. Icing Cloud Percent Melt Estimates

Research in the field of single frozen droplet melting characteristics has been conducted by Sihong and Palacios [42]. Data was collected on the melting rates of single frozen droplets suspended via an ultrasonic levitator, and luminescent dye in the water was used to measure the percent melt ratio. Data was collected for droplets from 0.3mm to 1.8mm and air temperatures from 5.2 °C to 25.4 °C, and an empirical model was developed, as seen in Figure 3-11. The temperature range tested for the single particle covers the same range as the duct temperatures for the cloud experiments, but the size of the single particles was an order of magnitude larger.

![Figure 3-11. Melt Rate Trends for single frozen droplets [42]](image)

This empirical model was used to estimate the percent melt of the cloud after exiting the duct. It was assumed that the sensible heat was much less than the latent heat, so time required for the cloud particles to warm from the tunnel temperature to the duct temperature was much less than the time to melt, so that sensible heat change time was ignored. The model was extrapolated
to a diameter of 0.024mm to match the MVD of the cloud. The cloud percent melt was calculated by multiplying the percent melt rate from the model by the time the cloud spent in the duct. As mentioned, for an air speed of 20m/s and a duct length of 1.4m, the cloud was in the duct for 0.07s. As was discussed earlier, the MVD for the cloud was 24µm, with most of the droplets falling between 10 µm and 50 µm. The empirical percent melt rate equation provided by Sihong et al. was used to determine the percent melt at the exit of the duct for the entire range of droplets sizes in the cloud. As seen in Figure 3-12, there was an exponential increase in percent melt as the temperature increases and the particle diameter decreased.

![Figure 3-12. Cloud percent melt at duct exit](image)

For simplification, the MVD percent melt was used to quantify the percent melt of the cloud. As seen in Figure 3-13, the percent melt for the 25µm droplets ranges from 2% at the lowest duct temperature to 20% at the highest duct temperature.
The accuracy of this empirical model for small droplet sizes was questioned because the effect of humidity was ignored, and the range of extrapolation from 800µm droplets to 25µm was extreme. The NASA Glenn mix-phase cloud code was also used to predict the melt ratio at the exit of the duct. The primary inputs to the simulation were particle size distribution, IWC, velocity, RH, air temperature, and initial particle temperature. Humidity data was not available for every test case, but it was seen that SH was constant at 1.12 g/kg with a 5% standard deviation for the environments tested. The appropriate RH was calculated to match the duct temperature and SH. The RH dependence on temperature can be seen in Figure 3-14. The ambient pressure measured constant at 977 hPa during testing, the particle distribution was taken from the PDI data, and the initial particle temperature was assumed to be -10ºC.
The results from the simulation provided by the NASA model were significantly different than those obtained from the empirical model, as seen in Figure 3-15. In the NASA code simulation, the particles did not start to melt until the duct temperature was above 6°C. In the empirical model, the particles started to melt at any temperature greater than freezing. At 24 °C duct temperature, the simulation predicted 89% melt and the empirical model predicted only 16% melt. The difference between the two models shows the importance of humidity effects. The duct temperatures taken during the experiment were converted to percent melt using a fifth order polynomial fitted to the simulation results.
The ice accretion rate as a function of percent melt provided by the NASA prediction tool can be seen in Figure 3-16. Once again, there is no clear correlation between accretion rate and percent melt for these cases.

![Figure 3-16. Accretion rate vs % Melt predictions from NASA Glenn Mixed-Phase cloud simulation](image)

3.5. Individual Case Observations

3.5.1. Particle Bounce Off

Cases 10a and 19c had no ice accretion but had a thin layer of very poorly adhered ice particles. The conditions for Case10a were 4.0°C duct temperature and -4.5°C plate temperature. The conditions for Case19c were 5.5°C duct temperature and -2.5°C plate temperature. As seen in Figure 3-17, a few large ice masses accreted to the plate primarily in the bottom left corner. Video evidence showed that ice came as large chunks from upstream and did not build up from the cloud.
Figure 3-17. Case 10a & 19c posttest surface photos

Case 26a and 27f both had a small region of rime ice buildup on the left side of the plate, as seen in Figure 3-18. That ice formation was ignored because the surface temperature of the plate in that area was not controlled. The surface temperature for both cases was close to zero. The ice growth in the uncontrolled region was attributed to surface temperature in that area to be above freezing due to the impinging hot duct air.

Figure 3-18. Case 26a & 27f posttest surface photos
3.5.2. Ice Accretion – Rough Surface

Ice accreted at lower plate temperature resembled traditional rime ice accretion. The ice texture was rough, and the color was opaque white, as seen in Figure 3-19. The case with accretion at the lowest duct temperature was case 27e. The plate and duct temperatures were 0 °C and 5 °C respectively. This case provided a clear transition between case 27f and 27g. During case 27f, ice only formed in the uncontrolled area where the plate was relatively warm. The surface temperature for case 27e was 0°C, 1°C warmer than case 27f and 1°C colder than case 27g, where the ice melted off. A plate temperature of 0°C was key to accreting ice at a duct temperature around 5°C. Case 28i had the same plate temperature as case 27e and the same duct temperature as case 12b, and showed the same rime ice characteristics. Case 20b was the warmest duct case that had uniform rime ice. These four cases mark the edges of the rime ice region.
The temperature and humidity time histories for case 12b are shown in Figure 3-20. The tunnel temperature increased from -10.5°C to -8.5 °C during the icing time. A 1.0 °C to 3.0 °C increase in free stream temperature was common for all cases because of air friction against the tunnel walls. The plate temperature was maintained at -4.0°C. The average wet bulb temperature was 2.0 °C with a 0.4 °C standard deviation. The average SH was 1.4g/kg with a 0.2g/kg standard deviation. The SH was 1.37 g/kg before the cloud was on and increased at a rate of 0.018 g/(kg
min) during and after the cloud was on. This small change in SH was neglected, and the SH was assumed to be constant.

![Figure 3-20. Case 12b time histories](image)

**3.5.3. Ice Accretion – Mixed Surface**

As the duct temperature increased, the water content in the cloud increased, and the ice surface started to transition to smoother ice shapes, as seen in Figure 3-21. Cases 28d, 29e, 28c, and 29b mark the corners of the “rime-glaze” transition region. Case 28d (9.5 °C duct and 0.5 °C surface) was the coldest duct temperature case that showed signs of mixed ice. The ice was more translucent ice than the colder duct cases, but the ice still had some noticeable surface roughness. Case 29e had the same plate temperature as case 28d, but the duct temperature increased to 15 °C and had similar characteristics. Case 28c had the same duct temperature as case 28d, but the surface temperature was reduced to -1.5 °C. The plate was able to pull more heat from the impinging cloud, so the rough ice areas were more dominant. The ice from case 29b (14.5 °C duct and -0.5 °C
surface) resembled case 28c more than 29e even though the conditions for 29b were closer to 29e. This demonstrates the rough surface ice presided at higher duct temperatures for lower surface temperatures because the Peltier could remove heat faster. Faster freezing promoted a rougher ice surface.

Figure 3-21. Case 28d, 29e, 28c, and 29b posttest surface photos

Reliable humidity data was obtained during case 28f. As seen in Figure 3-22, the tunnel temperature increased 3.0°C during the test, the surface plate was maintained at 0.0 °C, and the average duct temperature was 12.5 °C. The average SH was 0.9 g/kg, and the SH increases at the same rate, both before and after the cloud was turned on, so it can be concluded that no moisture
evaporated from the cloud. As discussed, the water content was too low, and the time the cloud was in the duct was too short for significant evaporation to occur. The increase in SH was attributed to the tunnel temperature increase. The free stream is always at 100% RH, so as it warms up the SH increases.

3.5.4. Ice Accretion – Smooth Surface

When the duct temperature was greater than 16.0°C, the ice surface was smooth, as seen in Figure 3-23. Case 37b, 28b, 29d, and 30c are examples of test cases representing the four corners of the smooth ice region. Case 30c was the only case in the smooth region tested that had a surface temperature below freezing. The melt ratio was highest for these cases, and the additional water smoothed the surface of the accreted ice. Case 38b had the highest duct and surface temperatures tested during this work and ice accretion was still possible. Case 38b highlights the cooling effect
that the incoming particles had on the ice accretion process. The light orange patch in case 37b was Kapton tape to hold a heat flux sensor seen in dark orange. The rectangular edge seen in case 30c was the heat flux sensor. The heat flux sensor was used for an unrelated test.

The humidity and temperature time histories are shown for Case37b in Figure 3-24. The average plate temperature during the icing event was 1.5 °C, but the surface temperature was initially 4.0°C, which decreased when the cloud impinged. At high duct temperatures, the Peltier did not have the power to maintain the desired temperature without the assistance of cooling from the partially melted cloud. The surface temperature was held constant at the set point once the
cloud was turned on. Similar to case 12b, there was a very small rise in SH during icing. The rate was 0.036 g/(kg min).

![Figure 3-24. Case 37b time histories](image)

### 3.5.5. Water Runoff Cases

The plate temperature of case 27g was only 1°C warmer than case 27e, but ice was not able to persist. The temperature of the plate dropped when the cloud first interacted with the plate, and the Peltier control system was not able to increase the temperature back to 1°C for 30 seconds. Frames segmented from the test video can be seen in Figure 3-25. Initially, rime ice was able to accrete on the left edge of the plate, as in cases 26a and 27f, but was more substantial. Ice accreted for 30 seconds until the plate temperature returned to 1°C. By 40 seconds, the frost in the middle of the plate started to melt. After 60 seconds, most of the ice had melted but had not slid off the plate. From 60 seconds to 90 seconds the ice and water slid outward until the center of the plate was clean, and by 120 seconds the entire Peltier region was free of ice and stayed clear for the
remainder of the test. Case 27g is a clear example of the edge of the envelope separating ice accretion due to partially melted ice particles and water run-off events.

![Figure 3-25: Case 27g video segments](image)

Case 36c was a unique case where ice accreted, melted off, then accreted again. The average plate surface temperature was 2°C, and the average duct temperature was 13 °C during icing. Case 36c is an example right on the boundary between ice accretion and water runoff. A time history of the plate surface temperature can be seen in Figure 3-26. Prior to the icing cloud turning on, the Peltier was not able to maintain the plate at the set point of 2°C. At 100% power the plate was maintained at 5°C. The plate temperature reached 2°C one second after the cloud came on, but the temperature continued to fall and leveled off at 0.9 °C after 13 seconds. The Peltier controller was slow to react given the small error and did not recover to the set point until 50 seconds into icing. The plate was maintained at 2.0 °C ±0.5 °C for the remainder of the test.
Frames from the video for Case 36c were taken during critical times and shown in Figure 3-27. Solid ice immediately started to form in the bottom right corner of the plate and was clearly visible by 5 seconds. Between 5 and 30 seconds, the area of the accretion reduced as warm water ran down the plate. At 30 seconds, the plate surface temperature started to recover, and the ice accretion debonded and started to slide down the plate. The ice mass slid off the edge of the plate after 45 seconds of icing. From that point to 105 seconds of icing, all of the incoming cloud melted and ran off the plate. A small patch of ice started to accrete at 105 seconds and persisted for the remainder of the test. The ice thickness at the end of the test was not measurable because it was too thin. The conditions of this test were in the transition region between water runoff and solid ice accretion. Case 36c was placed in the water runoff group because the initial large ice accretion melted away and the final ice accretion was too small to measure.
The case with the highest duct and plate temperatures was case 54a. Surprisingly, a thin layer of ice was able to accrete for a brief moment. Images taken from the test video are shown in Figure 3-28. The thin ice layer area was maximal at 2.5 seconds of icing, but it had melted to half the area by 4.0 seconds of icing. By 5.0 seconds, all of the ice had melted off. After 7.0 seconds, the excess had run off, and steady state ice particles melted and runoff process had started. No ice accreted for the remainder of the test. The ice only lasted for 5.0 seconds for case 54a which was significantly faster than case 27g. The surface temperature for case 27g initially dipped into the accretion region then recovered to the water runoff region. This was not the case for 54a.
The surface temperature time history for case 54a is shown in Figure 3-29. The surface temperature was 8.5 °C when icing started, but decreased to 4.8 °C within 3 seconds. The plate reached a steady 7.0 °C by 40 seconds well after the ice had melted. The surface temperature never dropped below 3.0 °C, the upper limit for ice accretion at high duct temperatures.
4. Comparison of NASA Glenn Mixed-Phase Model to Single Particle Melt Experiments

NASA Glenn has developed a numeric model to simulate the freezing and melting processes of a cloud inside a wind tunnel [29]. It was originally intended to simulate the melting processes that occur inside the NRC RATFac [29]. The predictions were also used to model the melting processes created in the NASA PSL [29]. The tool uses a time marching scheme to solve the conservation of mass, momentum, and energy as the cloud passed through a control volume. The simulation monitors tunnel geometry, air speed, atmospheric pressure, air temperature, SH, RH, droplet distribution, TWC, initial melt ratio, and initial droplet temperature. The model has not been directly validated for the melting time of particles [29]. There is currently no way to directly measure the melt ratio of a cloud, but research has been conducted in the experimental investigation of single particle melt dynamics. Yan et al. developed a technique to quantify the partial melting of levitating particles using an ultrasonic levitator and luminescence ink [42]. The intensity of the luminescence ink was correlated to the water content of the particle. This technique developed by Yan et al. was expanded in this research to collect more accurate environmental conditions, specifically the specific humidity surrounding the droplet. The additional information was critical for attempting to correlate to NASA’s melting prediction tools. The results from the single particle melting experiments were compared to the simulation and are presented in this chapter.

4.1. Experimental Setup

The experiments on single particle melting were done in collaboration with another graduate student, Miguel Alvarez. The core of the experiment was an ultrasonic levitator from tec5 [43]. The levitator used a piezoelectric actuator to bounce 58kHz acoustic waves off a reflector.
As seen in Figure 4-1, the sound pressure was able to exert a force on the droplet to levitate it. A 0.05g/L solution of rhodamine b was sprayed into the levitator and droplets formed at the nodes of the wave. The droplet size was roughly controlled by the amount of water sprayed. A 532nm green laser was used to illuminate the dye, and the water emitted orange 593nm light given the luminescent properties of the ink.

![Figure 4-1: Acoustic levitator schematic](image)

A schematic of the set up can be seen in . The levitator, cameras, lights, and mirror were attached to an optical table via translational stages for accurate positioning. A dichroic mirror was used to aim the 532 nm green laser and act as a filter when the computer vision camera was in position one. When computer vision camera was at position two, a filter was used to only pass orange light. The position of the camera had no effect on the ability to quantify percent melt, which was done by comparing the intensity of the luminescent ink to that of the fully melted droplet. A SenTech machine vision camera was the primary camera used to monitor the droplet melting process with an acquisition rate of 60Hz and was calibrated to 135 pixel/mm. A Phantom MIRO 310 high speed camera was only used for verification of the melting process. The MIRO was run
at 60Hz to match the Sentech, but the MIRO resolution was 1280x800 pixels which was 3.3 times higher resolution.

Cold nitrogen gas at 10kPa was used to freeze the levitating water droplets. Two 1.0L dewars were filled with liquid nitrogen and a copper coil was submerged to act as a heat exchanger. Pure nitrogen gas was sent into the copper coil tubing. The selection of nitrogen was done to eliminate trace gases that might freeze in the heat exchangers. A mixing valve was used after the heat exchangers to exhaust half the nitrogen to reduce the velocity at the exit of the 1.3 cm pipe. A low airspeed was required or the droplet would be blown out of the levitator. A Li-Core 840A gas analyzer was used to measure specific humidity near the levitator. A vacuum pump pulled air into the analyzer, and the air inlet was attached to the cold air pipe 3.0 cm away from the droplet. Two thermistors were used to monitor the temperature near the droplet. One was placed at the exit of the cold air duct, and one was placed on the opposite side of the reflector each 1.0 cm away from the droplet. The average temperature was used to calculate RH.

Figure 4-2: Single particle experimental setup.
4.2. Results

During the experiment, total light intensity, SH, and temperature were measured and percent melt and RH were calculated. Total light intensity was recorded during the freezing and melting processes, as seen in Figure 4-3. The total intensity was calculated by recording the RGB values from the camera, converting to grayscale, then summing the intensity values for every pixel. Turbulence in the cold air flow made the particle vibrate during the cooling processes (due to the blowing of the nitrogen gas), causing noise and inaccurate intensity readings. For this reason, the 100% water intensity level was taken prior to turning on the cold air, and the 100% ice intensity was taken once a steady state minimum value of luminescence was reached. These two intensities were used to scale the total intensity linearly to calculate a melt ratio. Prior the initialization of melting, it was confirmed visually that the water droplets were fully particleized.

![Figure 4-3: Case 13 light intensity time history](image-url)
During testing, it was observed that there was a peak in light intensity (up to 25% over the steady state water state). Video evidence showed that the actual 100% water state was at the peak intensity, but the amount of ice present at the calculated 100% melt value (before the unexpected peak) was negligible. It was hypothesized that the overshoot and subsequent decay in intensity was attributed to dye mixing and light quenching. Light quenching occurs when the concentration of dye is too high and the light emitted from one molecule is absorbed by another. Frames taken from the case13 video are shown in Figure 4-4. The droplet was steady for the first 7s before the cold nitrogen turned on and the intensity data was reliable. From 7s to 41s the cold nitrogen was on and the droplet froze, but the intensity data was not reliable because the frame rate of the camera was too slow to freeze the vibrating droplet’s motion. At 41s the nitrogen was turned off, and the particle melted. The droplet melted to 50% at 43s and 100% at 46s. The maximum intensity peaked at 48s, and steady state intensity was reached at 55s.
A sample of humidity data can be seen in Figure 4-5. The SH during the test was constant because the air inlet for the SH sensor was not close enough to the droplet to be effected by the cold nitrogen flow. The RH increased while the cold flow was on because the temperature sensors were cooled by the cold air. The RH data taken while the cold air was flowing was not valid because the temperature and SH data were not taken from exactly the same location in space.
A sample temperature time history can be seen in Figure 4-6. It can be seen that the temperature close to the cold flow is colder than the sensor on the far side of the levitator. The intensity showed the droplet froze at 30s, but thermistors were reading above freezing at that time. The mass of the thermistors affected their temperature reading. The limited cold flow over the sensors required additional time for the sensor to cool to the flow temperature. The steady state temperatures were the only reliable temperatures and were used for melting calculations.
Finally the percent melt calculated from the experiment was compared to the NASA model, as seen in Figure 4-7. When the particles melted quickly, the NASA model tended to take longer to melt than the experiment. An example of this observation is seen in case 13 in Figure 4-7. It will be shown in a later section that inaccurate temperature measurements (related to the mass and location of the sensor) could have caused the difference in melt time. It was also seen that the model predicted a smooth transition from ice to water. On the contrary, the experiment provided highly nonlinear results, raising questions about the accuracy of the linear relationship between total intensity and percent melt assumption used when using the rhodamine b technique.

![Figure 4-7: Case 13 comparison of experiment and model melt time.](image)

A total of 15 cases were tested, as seen in Table 4-1. The particle diameters ranged from 1112 µm to 324 µm, the temperatures ranged from 15°C to 27°C, and the RH ranged from 60% to 100%. The particle sizes tested were an order of magnitude larger than the particles expected in the low pressure compressor region, but particles smaller than 300 µm could not be tested. Smaller droplets were unstable in the levitator and would fall out, or they would evaporate. The first seven cases had larger particles, higher RH, and lower temperatures, so the melt time for the first set was longer than the following cases. Case 4 should be ignored because of high noise in the intensity signal due to high particle vibration during the melting process.
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<td>60</td>
<td>5</td>
<td>9</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>703</td>
<td>24</td>
<td>67</td>
<td>7</td>
<td>9.5</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>762</td>
<td>27</td>
<td>61</td>
<td>5</td>
<td>9.5</td>
<td>90</td>
</tr>
<tr>
<td>12</td>
<td>709</td>
<td>29</td>
<td>50</td>
<td>4</td>
<td>8.5</td>
<td>113</td>
</tr>
<tr>
<td>13</td>
<td>634</td>
<td>30</td>
<td>45</td>
<td>4</td>
<td>7</td>
<td>75</td>
</tr>
<tr>
<td>14</td>
<td>601</td>
<td>31</td>
<td>41</td>
<td>3</td>
<td>6.1</td>
<td>103</td>
</tr>
</tbody>
</table>

The melt times are compared in Figure 4-8. The cases that melted slower than ten seconds had a discrepancy between test and model of 13% while the cases that melted faster than 10 seconds had 64% discrepancy between the model and experiment. The time difference between the model and experiments was at most 4.5 seconds. This error was acceptable given the complexity of the experiment and the fact that the model was coded to model cloud thermal dynamics and not to represent single particles, as it was experimentally evaluated.
4.3. NASA Glenn Mixed-Phase Code Introduction

The simulation numerically time marches the conservation of mass, momentum, and energy equations for a cloud in a wind tunnel. Some of the important assumptions of the model were: one dimensional flow, ideal air and water, adiabatic control volume, spherical droplets, no coalescence or breakup of droplets, uniform temperature in the droplets, and spatially homogeneous mixed phase droplets. The water vapor mass gained or lost from the air was set to be equal and opposite to the change in mass of the droplets. As seen in Equation 4-1, the mass transport is dependent on the phase change at the surface of the droplet (evaporation/condensation) where $\omega$ is the water vapor mass fraction, $D$ is the droplet diameter, $h_m$ is the mass transfer coefficient of water vapor, and $\rho$ is the air density. The energy balance in this problem was between internal energy and the latent and convective heat flux, as seen in Equation 4-2. The empirical fittings from Dalton [44] were used to expand the terms in Equation 4-2 to develop Equation 4-3,

![Figure 4-8: Comparison of experimental and model melt time for all cases.](image-url)
which represents energy transfer from the water. The conservation of momentum was used to track the particle acceleration, velocity, and position in the tunnel. As seen in Equation 4-4, the acceleration of the droplets is dependent on the slip velocity between the droplets and the air. The drag force accelerates the droplets to the flow speed. The slip velocity for the particles in the tunnel duct was zero because the particles flow with the air, and the slip velocity was zero for the levitating single particle experiments because only natural convection occurred.

\[
\frac{\partial m_{air}}{\partial t} = - \frac{\partial m_p}{\partial t} = \pi D^2 h_m \rho_{air} (\omega_p - \omega_{air}) \quad \text{Equation 4-1}
\]

\[
\frac{\partial H_p}{\partial t} = q_{conv} + q_{latent} \quad \text{Equation 4-2}
\]

\[
\rho_p C_p \frac{\pi d^3}{6} \frac{\partial T_p}{\partial t} = \pi D^2 h (T_{air} - T_p)
+ \pi D^2 h_m \rho_{air} L_{evap} (\omega_{air} - \omega_p) \quad \text{Equation 4-3}
\]

\[
\frac{\partial V_p}{\partial t} = \frac{3 V_{air} C_D (V_{air} - V_p)^2}{4 \rho_p D} \quad \text{Equation 4-4}
\]

4.4. Model Assumptions and Sensitivity

This model was written to simulate clouds in a tunnel, but it was compared to single droplet experiments. The two big differences between the experiment and the model were the droplet size and TWC. The model assumes the temperature in the droplet is constant. For this assumption to hold, the Biot number must be less than the critical number of 0.1. When the Biot number is less than the critical number, the conductive time scale in the particle is much less than the surface heat transfer time scale, so heat on the surface is instantly transferred though the particle. Biot number is based on the droplet diameter \((D)\), the free heat transfer coefficient \((h)\), and the thermal
conductivity \((k_p)\) as seen in Equation 4-5. The heat transfer coefficient was calculated from the Nussult number \((Nu)\) for natural convection around a sphere [45] as seen in Equation 4-6. The Nu is the ratio of total heat transfer to conductive heat transfer where \(h\) is the heat transfer coefficient, \(D\) is the particle diameter, and \(k_{air}\) is the thermal conductivity of air. The \(Nu\) for natural convection around a sphere is dependent on the Prandtl number \((Pr)\) and Rayleigh number \((Ra)\). The \(Pr\), seen in Equation 4-7, is the ratio of viscous diffusion rate to thermal diffusion rate, where \(v\) is the kinematic viscosity, and \(\alpha\) is the diffusivity. The \(Ra\), as seen in Equation 4-8, is a function of gravitational acceleration \((g)\), the thermal expansion coefficient \((\beta)\), particle surface temperature \((T_{surf})\), far field temperature \((T_{\infty})\), particle diameter \((D)\), kinematic viscosity \((v)\), and diffusivity \((\alpha)\). From this set of equations the Biot number was calculated. The largest droplets tested were 1000 \(\mu m\) and the Biot number for those was 0.004 for frozen droplet and 0.014 for a liquid droplet. It was safe to assume the temperature in the droplets was uniform for all the droplets tested.

\[
Bi = \frac{hD}{6k_p} < 0.1 \quad \text{Equation 4-5}
\]
\[
Nu = \frac{hD}{k_{air}} = 2 + \frac{(0.589Ra^{1/4})}{\left(1 + \left(\frac{0.469}{Pr}\right)^{9/16}\right)^{4/9}} \quad \text{Equation 4-6}
\]
\[
Pr = \frac{v}{\alpha} \quad \text{Equation 4-7}
\]
\[
Ra = \frac{(g\beta(T_{surf}-T_{\infty})D^3)}{v\alpha} \quad \text{Equation 4-8}
\]

The initial temperature for the particles in the model was set to -11.0 \(^\circ C\), but the actual particle initial temperature was unknown. The initial particle temperature does not affect the melt time because the melt time was defined as the time of phase change. It started when the particle reached 0\(^\circ\)C and stopped when it rose above 0\(^\circ\)C. The initial particle speed and air speed were set to 0 m/s because there was no flow over the particle while it melted in the levitator. The TWC for
the single droplets ranged from $1.78 \times 10^{-8}$ to $7.2 \times 10^{-7}$ g/m$^3$. A TWC convergence study was necessary to see how the model reacted to TWC orders of magnitude lower than that of a natural cloud. For the TWC study, the droplet diameter was 420 µm, the temperature was 16ºC, and the RH was 10%. As seen in Figure 4-9, the change in melt time related to a variation of TWC from 1.0 to 0.005 g/m$^3$ was 0.6 second. Decreasing the TWC below 0.005 g/m$^3$ had no effect on the melt time. It should be noted that the model required a distribution of droplets with at least 7 different droplet sizes or bins. To simulate a single drop, the center bin was set to the droplet diameter and had a 94% weight. The other six bins were incremented up and down by 1 µm from the center bin and had a 1% weight. Using the actual TWC for one droplet, the model was calculating fractions of droplets because of the distribution. When the TWC was increased by two orders of magnitude to make sure there were no fractional droplets, the melt time was the same. The melt time was not sensitive to TWC when the TWC was less than 0.01 g/m$^3$ and the fact that the model calculated fractions of particles at the actual TWC had no effect on the melt time.

![Figure 4-9: TWC convergence](image)

Figure 4-9: TWC convergence
Next the sensitivity of the model predictions due to droplet diameter variations was studied. The particle diameter was varied from 250 µm to 1000 µm with an air temperature of 20°C, 60% RH, and 5.24 x10^-7 TWC. As expected, the melt time increases with droplet size, but it is not linear as seen in Figure 4-10. Melt time changed by an order of magnitude over the range of particle sizes, but the local sensitivity, given by the slope of the melt time to particle diameter relationship, was low. The average sensitivity of 0.035 s/µm provided minimal discrepancies in the calculation of melting time when calculating particle size.

![Melt Time vs Particle Diameter](image1)

![Local Sensitivity](image2)

*Figure 4-10: (a) Melt time vs particle diameter (b) local sensitivity.*
The melt time sensitivity to RH was also evaluated. The RH was studied from 20% to 80% with a temperature of 20°C, a TWC of $1 \times 10^{-7}$, and a particle diameter of 421 µm. As seen in Figure 4-11, the melt time decreased with RH non-linearly. The average local sensitivity was -0.12 s/RH. Uncertainties in calculating RH could therefore affect the melt time predictions more than particle size variations, but the effect was still small.

![Figure 4-11: (a) Melt vs RH (b) local sensitivity.](image)

Evaporation and condensation are the reasons melt time decreased with RH. As seen in Figure 4-12, the cases with 40% or higher RH immediately started to condensate and collect water. The extra water increased the melt ratio without melting the particle. Below 40% RH, the water that melts evaporates, effectively reducing the melt ratio.
The last model input studied was air temperature. The air temperature was varied from 10°C to 30°C with a TWC of 1 x 10^{-7} g/m³, a RH of 50%, and a particle size of 600 µm. Over this range of temperatures, the melt time decreased by a factor of 10 as seen in Figure 4-13. The local sensitivity ranged from -5.5 s/°C to 0.5°C which was the highest sensitivity studied. The high sensitivity to temperature was deemed to be the greatest cause of uncertainty between the model and experiments.
The sensors used in the experiment were only accurate to 1ºC or 2ºC which gives an error of 1s to 2s in the temperature ranged tested. To evaluate the accuracy of the thermistors, 9 identical thermistors were placed in a temperature controlled environment, and the steady state temperatures were recorded for a range of ambient temperatures. The ambient temperature varied from 28.0°C to 43.0°C. The average temperature for each case is plotted in Figure 4-14 with minimum and maximum bars. The maximum difference from the hottest to coldest thermistor was 1.4 ºC, the minimum difference was 0.3ºC, and the average difference was 0.7ºC. The thermistors must each be calibrated to increase the accuracy to an acceptable level. For most applications an accuracy of 1.0ºC is tolerable, but this research need to be within 0.1ºC.
Figure 4-14: Thermistor accuracy (average temperature with min/max bars)

4.5. Model Comparison Summary

Single particle melt tests were compared to the NASA Glenn mixed-phase cloud melt model. It was seen that the cases that melted slower than ten seconds was 13% discrepancy while the cases that melted faster than 10 second had 64% discrepancy between the model and experiment. The melt time difference between the model and experiments was at most 4.5 seconds. The sensitivity of the model to TWC, particle diameter, RH, and air temperature were studied, and air temperature had the highest sensitivity with 1 s/ºC in the temperature region of the experiments. The temperature sensor accuracy and model sensitivity to air temperature were the causes of uncertainty, given the thermal load of the thermistor used and the impossibility to place a temperature reading exactly where the droplet is levitating. The approximation that the total intensity of the rhodamine b was linear with percent melt may not be accurate. Despite mentioned shortcomings related to the complexity of the experimental set-up, the model has been correlated within the experimental capabilities available during this research.
5. Conclusions and Future Work

5.1. Facility and Ice Accretion Conclusions

The ambitious goal to build a novel mixed-phase icing tunnel that could freeze then partially melt a cloud continuously in the flow was achieved. An unconventional wind tunnel configuration was designed and fabricated as a semi closed loop circuit with the two ends of the tunnel meeting at opposite ends of a freezing chamber. The freezer accommodated two independent cooling systems. For this research, the tunnel temperature was maintained at -11°C. A 125 HP motor was able to drive the flow over 40 m/s at the 0.93m by 0.62m test section. For this research, the air speed was maintained at 20 m/s due to limits of the cooling system related to kinetic heating and input air mass flow of hot air used to melt the particle cloud. The testing time was limited to 2.5 minutes for the same reasons. The cloud was generated using NASA standard icing nozzles. Expansion cooling and convection were used to glaci ate the water droplets in the cloud. The water pressure supplied to the nozzles was five times greater than the ambient pressure. The water droplets cooled significantly as the pressure dropped and continued to freeze while traveling down the tunnel. The particle size distribution was calibrated by NASA given a specific air and water pressure. A Phase Doppler Interferometry was used to verify the particle distribution, and the Median Volume Diameter (MVD) of the nozzles used in this facility matched the latest NASA calibration. A particle size of 23 µm was selected to enhance the ability to freeze the cloud and represent realistic sizes seen in an engine, as determined by previous research.

A hot air injection system was developed to partially melt the ice particle cloud. A 1.4 m duct was positioned in the center of the tunnel, upstream of the test section, so the exit of the duct was 6.0cm upstream of the test section center. Three 18 kW air heaters were used in parallel to generate the hot air needed to partially melt the fully glaciated cloud. The hot air was introduced
to the duct through a distribution ring that had eight evenly spaced hot air injection ports. A PID system maintained a desired temperature in the distribution ring to achieve the required duct temperature. The duct temperature could vary from the tunnel temperature (-11°C) to a maximum of 24.0°C. Accretion tests were conducted at duct temperatures ranging from 3.5°C to 24.0°C. Using the NASA Glenn mixed-phase model, it was seen that the duct produced mixed phase clouds having 0 to 90% partial melting. A gas analyzer was used to monitor the humidity at the duct exit. It was seen that the specific humidity was constant for every test at 1.12 g/kg with a 5% deviation. The wet bulb temperature for the cases studied ranged from 1.0°C to 7.5°C. Positive wet bulb temperatures meant the particles had a tendency to melt rather than freeze, but significant ice accretion did occur given the subfreezing temperatures maintained on the accretion plate.

A flat plate accretion surface was fabricated using a Peltier cooling system to maintain a constant surface temperature. Two 4.8 cm by 2.4 cm Peltier semiconductors were placed behind a 1.2 mm thick sheet of aluminum, and a liquid cooled heat sink removed waste heat form the Peltiers. The surface temperatures tested ranged from -4.5°C to 7.0°C.

Forty-eight ice accretion tests were conducted, and the boundaries between the water runoff, ice accretion, and particle bounce off were determined. If the duct temperature was below 7.0°C and the plate surface was at or below freezing, the ice particles did not melt and they bounced off the surface off the plate. Some particles did latch onto the surface building a thin layer of frost, but it was not adhered and could be brushed off. The boundary between the ice accretion and water run off regions changed linearly in the duct vs plate temperature plane. As the duct temperature increased, the maximum plate temperature at which ice accreted increased. The cooler end of the boundary started at 5.5°C duct temperature (1% melt) and 0°C plate temperature and increased to
3.0°C plate temperature (90% melt) at 24°C duct temperature. Above this boundary, all the incoming particles melted and flowed off the plate.

In the ice accretion region, there were two distinct types of ice with a transition zone in between. The first type of ice was opaque in color and had a rough surface. This ice occurred roughly from 6.0°C to 12.0°C duct temperatures (8% to 50% melt). The exact bounds can be seen in chapter 3. The qualitative characteristics of the ice were produced from the low water content in the cloud. The water that was available froze instantly and trapped ice particles. Duct temperatures greater than 17.5°C (80% melt) produced ice that was clear and smooth. The water in the surface did not freeze instantly due to the high water content creating a water film that froze. The ice accretion between these two zones had mixed properties from both types of ice. This data has shown that the Penn State Icing Tunnel (PSIT) is capable of generating a fully glaciated cloud, for which it can then partially melt the ice particle cloud from 0% to 90%. This is the first facility to generate and melt an ice particle cloud through natural convection. The combinations of plate temperature and particle percent melt where ice can accrete has been shown, and two different icing types have been observed.

5.2. NASA Glenn Mixed-Phase Model Comparison Conclusions

The final part of this research was focused on comparing the NASA Glenn mixed-phase model to single particle experiments, and it has been shown that the model matched the experiments within the accuracy of the data collected. Water droplets dyed with a 0.05g/L solution of rhodamine b were suspended with an acoustic levitator. The droplets were fully frozen with a cold flow then melted under natural convection when the flow was shut off. The light intensity released from the dye was monitored to determine the percent melt. The time to reach 100% melt
was compared to the NASA model used to predict partial melting in the PSIT icing cloud. 15 droplets were tested with diameters ranging from 1112µm to 324µm, air temperatures varying from 31°C to 16°C, and RHs measured between 41% and 100%. The average discrepancy between predictions and results for the cases that melted slower than ten seconds was 13% discrepancy while the cases that melted faster than 10 second had 64% discrepancy between the model and experiment. The primary reason for this discrepancy comes from the inability to measure the atmospheric conditions in the immediate area around the droplet, the potential nonlinearity between total light intensity emitted form the dye, and the intensity overshoot observed during testing. Due to space constraints, the temperature sensor was placed 1 cm away from the droplet and the humidity sensor was sampling air 3 cm from the droplet. Parametric studies showed that a one degree change in temperature would change the melt time by one second for an air temperature of 30°C. The melt time sensitivity to RH was -0.05s/RH for 80% and 0.275s/RH for 40%. The RH sensitivity was less than the temperature sensitivity, but the air sample was taken farther away and temperature was used in the calculation for RH. The sensitivity for droplet diameter was an order of magnitude less then RH, and the sensitivity for TWC was 0 for TWCs less than 0.01 g/m³. The intensity overshoot was attributed to transient effects of rhodamine b as the droplet melts. The physics of the transient behavior of the rhodamine b is not understood. A 2.7s difference between model and experiments was acceptable given the model sensitivity to temperature, the difficulty in measuring temperatures at the position of the droplet, and the transient characteristics of rhodamine b.
5.3. Future Work

The flat plate accretion data is valuable for fundamental partially melted ice accretion model validation, but a flat plate is not a shape that is representative of a compressor blade. Research will be conducted on airfoils to more closely match the flow field in a compressor. The airfoil chosen can be seen in Figure 5-1. It is symmetric foil with a 12 inch chord and 2 inch thickness located in the mid chord. The temperature of the leading edge will be controlled by blowing air through a perforated duct, so the air will impinge in the inside of the leading edge.

Figure 5-1: Mixed phase accretion airfoil

The temperature of the air going to the duct is controlled via a three-way valve where hot and cold air are mixed proportionally, as seen in Figure 5-2. Cold air is generated with a liquid nitrogen (LN2) heat exchanger. A copper coil is submerged in dewar filled with LN2. The resultant cold air temperature can vary from 0°C to -100°C depending on the depth of nitrogen. Hot air is generated with a 750W air process heater that can generate air up to 100°C. A pneumatically driven 3-way mixing valve controls the proportions of hot and cold air to control the temperature of the airfoil leading edge. A PID controller receives temperature data from the airfoil and changes the mixing valve accordingly.
The single particle melting experiment can be improved by increasing the accuracy of the temperature sensors. A smaller, more reactive probe is required. The h1744 polyimide thermistor from U.S. Sensor Corp. might be a suitable replacement. The diameter of the h1744 is 30% smaller and the length is 40% shorter than the current EPCOS B57861S202F40 thermistor, as seen in Figure 5-3 [46,47]. The smaller thermistor will have a faster reaction time and could be placed closer to the droplet. A smaller sensor should give more accurate data, but the sensor will not go directly next to the droplet because it would interfere with the acoustic waves.
An infrared (IR) camera could collect data on the surface temperature of the particle. The surface temperature cannot be used to determine the melt ratio, but it could be used to determine the start and stop times of the melt process. The lumped capacitance method assumes the droplet temperature is homogeneous, so the droplet temperature has to be 0°C during phase change, as seen in Figure 5-4. An IR camera such as the FLIR A8300sc would be able to detect this change in temperature and verify the total melt time. The FLIR A8300sc has a 60Hz frame rate at 1280x720 pixels. The 4x close up lens has a field of view of 4.4x2.5mm, leading to a calibration of 5632 pixels/mm. The capabilities of this camera should be more than necessary for this experiment.

Figure 5-4: Sample droplet temperature during melting
References


[44] J. Dalton, Experimental essays on the constitution of mixed gases; on the force of steam or vapor from water and other liquids in different temperatures, both in a Torricellian vacuum and in air; on evaporation and on the expansion of gases by heat, Mem. Proc. Manchester Lit. Philos. Soc. 5 (1802) 535–602.


Appendix: Matlab processing code

clear all; close all; clc;

cd('Z:\AERTS Test Data\Particles Wind Tunnel\Accretion Data')
cf = pwd;
D = dir;
folder_num = length(D)-7;

W = waitbar(0,'Reading Data Please wait...');
step = 0;
final_step = folder_num;
ii = 1;
ww = 1;
kk = 1;
IceTotalRate = 0;
IceCase = 1;
for i = 1:folder_num

    step = step+1;
    waitbar(step/final_step)
    TunnelData = importdata(fullfile(cf, D(i+3).name, 'Tunnel Data.txt'));
    tunnel_data = TunnelData.data;
    start_time = 0;
    end_time = 0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 
%%find cloud start and stop time and index
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 

    for j = 1:length(tunnel_data)
        time = tunnel_data(j,1);
        ice_on = tunnel_data(j,19);
        if ice_on > 0 && start_time ==0
            start_time = time;
            start_index = j;
        elseif ice_on > 0 && start_time ~=0
            end_time = time;
            end_index = j;
        end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 
%%calculate average plate and Round to nearest 0.5
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 

    plate_temp_average = mean(tunnel_data(start_index:end_index,18));
    plate_temp_average = round5(plate_temp_average);

end
plate_temp_std =
    abs(std(tunnel_data(start_index:end_index,18))/plate_temp_average*100);
plate_temp_delta = max(tunnel_data(start_index:end_index,18)) -
    min(tunnel_data(start_index:end_index,18));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%%%%%%%%%%%%%%%%%%%%
%%calculate average Tunnel temp 
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%%%%%%%%%%%%%%%%%%%%
Tunnel_start_temp = tunnel_data(start_index,16);
Tunnel_stop_temp = tunnel_data(end_index,16);
Tunnel_mean_temp = mean(tunnel_data(start_index:end_index,16));
Tunnel_delta_temp = Tunnel_stop_temp - Tunnel_start_temp;
Tunnel_std_temp =
    abs(std(tunnel_data(start_index:end_index,16))/Tunnel_mean_temp*100);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%%%%%
%%%%%%%%%%%%%%%%%%%%
%%calculate average duct and Round to nearest 0.5   
%%simulate duct temp time hist by tracking duct time with tunnel temp 
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%%%%%%%%%%%%%%%%%%%%
duct_temp_start = mean(tunnel_data(start_index-30:start_index-20,6));
temp_diff = Tunnel_start_temp-duct_temp_start;
Duct_temp_sim = zeros(length(tunnel_data),1);
Duct_temp_sim(1:start_index-20) = tunnel_data(1:start_index-20,6);
Duct_temp_sim(start_index-19:length(tunnel_data)) = -
temp_diff+tunnel_data(start_index-19:length(tunnel_data),16);
Duct_temp_avg = mean(Duct_temp_sim(start_index:end_index));
Duct_temp_avg = round5(Duct_temp_avg);
Duct_temp_delta = Duct_temp_sim(end_index) - Duct_temp_sim(start_index);

if length(tunnel_data(1,:)) >21
    window_size = 50;
    end_index = end_index - window_size;
    start_index = start_index - window_size;
    PPT =
    filter(ones(1,window_size)/window_size,1,tunnel_data(:,22))*(28.9546/18.01528);
    PPT(1:window_size) = [];
    tunnel_data(1:window_size,:) = [];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%%%%%%%%%%%%%%%%%%%%
%%SH RH and wet bulb
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%%%%%%%%%%%%%%%%%%%%
for jj = 1:length(tunnel_data)
Tc = Duct_temp_sim(jj); \%C
P = tunnel_data(jj,20); \% kPa
P = P*10; \% mbar or hPA
Tw = -12;
EE = 100;

saturation_vapor_pressure = 6.112*exp((17.67*Tc)/(Tc+243.5));\%https://www.rsmas.miami.edu/users/pzuidema/Bolton.pdf

% MR = solve(SH(jj)==1000*x/(1+x),x);
% MR = -SH(jj)/(SH(jj) - 1000);
% VP = double(solve(MR==.622*y/(P-y),y));
MR(jj) = (PPT(jj)/1000)/(1-(PPT(jj)/1000))*(18.01528/28.9645);
VP = (500*MR(jj)*P)/(500*MR(jj) + 311);
RH(jj) = double(VP/saturation_vapor_pressure*100);
SH(jj) = 1000*MR(jj)/(MR(jj)+1); \%g_H2O/kg_TotalAir

while EE > 0.5
    Saturation_Vapor_Pressure = 6.112*exp((17.67*Tw)/(Tw+243.5));
    Vapor_Pressure = Saturation_Vapor_Pressure - (P * (Tc - Tw) * 0.00066 * (1 + (0.00115 * Tw)));
    Error = (VP-Vapor_Pressure)/VP*100;
    EE = abs(Error);
    if Error > 0
        Tw = Tw +.01*EE;
    else
        Tw = Tw -.01*EE;
    end
end

Wet_Bulb(jj) = Tw;
end

Twb_Mean = mean(Wet_Bulb(start_index:end_index));
Twb_std = std(Wet_Bulb(start_index:end_index));
SH_Mean = mean(SH(start_index:end_index));
SH_std = std(SH(start_index:end_index));
RH_Mean = mean(RH(start_index:end_index));
RH_std = std(RH(start_index:end_index));
else
    SH_Mean = nan;
    SH_std = nan;
    RH_Mean = nan;
    RH_std = nan;
    Twb_Mean = nan;
    Twb_std = nan;
end

time_step = tunnel_data(2,1) - tunnel_data(1,1);
icing_time = end_time - start_time;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% calculate average ice thickness from 2 to 5 cm

IceThickness = importdata(['
D(i+3).name '
'Ice Thickness.txt']);

if IceThickness(1,1) < 4
  IceThickness = flip(IceThickness);
end

for w = 1:length(IceThickness)
  position = IceThickness(w,1);
  thickness = IceThickness(w,2);
  if position >=5
    start = w;
  elseif position >=2
    stop = w;
  end
end

IceData = flip(IceThickness(start+1:stop,:));

Ice_Average = mean(Total_IceData(:,2))*10;
Ice_Max = max(Total_IceData(:,2))*10;

Rate_avg = Ice_Average/icing_time*60;
if Rate_avg == 0
  Rate_avg = .001;

Rate_max = Ice_Max/icing_time*60;

% calculate percent melt and round to nearest 0.5 (sihong)

MVD = .025;
Tair = Duct_temp_avg;
percent_melt_rate = (4e-3*Tair^2 + 0.14*Tair)/MVD;
duct_length = 1.4;
velocity = 20;
melt_time = duct_length/velocity;
PM = (percent_melt_rate*melt_time);
PM = round5(PM);

% calculate percent melt and round to nearest 5.0 NASA

if Duct_temp_avg >= 7
    PM = -6.46945E-04*Duct_temp_avg^5 + 5.24494E-02*Duct_temp_avg^4 -
    1.62756E+00*Duct_temp_avg^3 + 2.36240E+01*Duct_temp_avg^2 -
    1.50373E+02*Duct_temp_avg + 3.40024E+02;
    PM = round_5(PM);
else
    PM = 0;
end

% collect data

Accretion(i,:) = [Duct_temp_avg, Duct_temp_delta, plate_temp_average
,plate_temp_delta, Rate_avg, Rate_max, Tunnel_mean_temp, Tunnel_delta_temp,
PM, icing_time, SH_Mean, SH_std, RH_Mean, RH_std, Twb_Mean, Twb_std];
Name = {D(i+3).name};
Case = char(Name);
CaseName(i) = {Case(5:7)};

% organize into groups

if Rate_avg >.001
    IceGroup(ii,:) = [Duct_temp_avg plate_temp_average PM];
    IceTotalRate(IceCase) = Rate_avg;
    IceCase = IceCase + 1;
end
ii=ii+1;
elseif Rate_avg == .001 && plate_temp_average >0
    WaterGroup(ww,:) = [Duct_temp_avg plate_temp_average PM];
    ww=ww+1;
else
    ParticleGroup(kk,:) = [Duct_temp_avg plate_temp_average PM];
    kk=kk+1;
end

end
IceGroup(length(IceGroup)+1,:) = [8 0 8];
delete(W)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
%%print data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
Data_Table = table;
Data_Table.Case = CaseName';
Data_Table.Duct_Temp_avg_C = Accretion(:,1);
Data_Table.Duct_Temp_delta_C = Accretion(:,2);
Data_Table.Plate_Temp_avg_C = Accretion(:,3);
Data_Table.Plate_Temp_delta_C = Accretion(:,4);
Data_Table.Ice_Rate_avg_mm_min = Accretion(:,5);
Data_Table.Ice_Rate_max_mm_min = Accretion(:,6);
Data_Table.Tunnel_Temp_avg_C = Accretion(:,7);
Data_Table.Tunnel_Temp_delta_C = Accretion(:,8);
Data_Table.percent_melt = Accretion(:,9);
Data_Table.icing_time = Accretion(:,10);
Data_Table.SH_mean = Accretion(:,11);
Data_Table.SH_std = Accretion(:,12);
Data_Table.RH_mean = Accretion(:,13);
Data_Table.RH_std = Accretion(:,14);
Data_Table.Twb_mean = Accretion(:,15);
Data_Table.Twb_std = Accretion(:,16);
cd('Z:\AERTS Test Data\Particles Wind Tunnel')
writetable(Data_Table,'summary table.txt')

Tunnel_Temp_overall_mean = mean(Accretion(:,7))
Tunnel_Temp_overall_std = std(Accretion(:,7))
Mean_Ice_Rate = mean(IceTotalRate)
STD_Ice_Rate_Percent = 100*std(IceTotalRate)/Mean_Ice_Rate
number_of_cases = i

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
%%Plot data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

125
DuctMax = max(Accretion(:,1));
DuctMin = min(Accretion(:,1));
PlateMax = max(Accretion(:,3));
PlateMin = min(Accretion(:,3));
PmeltMax = max(Accretion(:,9));
PmeltMin = min(Accretion(:,9));

DuctLength = round((DuctMax-DuctMin)/0.5)+1;
PlateLength = round((PlateMax-PlateMin)/0.5)+1;

BarData = nan(DuctLength,PlateLength,5);    %% make 3d matric incase there are repeat data points
for k = 1:length(Accretion)
    ii = round(((Accretion(k,1)-DuctMin))/0.5)+1;
    jj = round(((Accretion(k,3)-PlateMin))/0.5)+1;
    if isnan(BarData(ii,jj,1))
        BarData(ii,jj,1) = Accretion(k,5);
    elseif isnan(BarData(ii,jj,2))
        BarData(ii,jj,2) = Accretion(k,5);
    elseif isnan(BarData(ii,jj,3))
        BarData(ii,jj,3) = Accretion(k,5);
    elseif isnan(BarData(ii,jj,4))
        BarData(ii,jj,4) = Accretion(k,5);
    elseif isnan(BarData(ii,jj,5))
        BarData(ii,jj,5) = Accretion(k,5);
    end
end

for ii = 1:DuctLength    %%average down to 2d
    for jj = 1:PlateLength
        BarData_avg(ii,jj) = nanmean(BarData(ii,jj,:));
    end
end

figure
b = bar3(DuctMin:0.5:(DuctMax),BarData_avg);
set(gca,'XTick',0:2:PlateLength)    %%Fix tick marks
set(gca,'XTickLabel',PlateMin-.5:1:PlateMax)    %%replace marker lables with plate temp
axis([0 25 0 25])
colormap('jet')
h = colorbar;

for iSeries = 1:numel(b)    %%remove 0 data
    zData = get(b(iSeries),'ZData');  %# Get the z data
    index = logical(kron(zData(2:6:end,2) == 0,ones(6,1)));  %# Find empty bars
    zData(index,:) = nan;    %# Set the z data for empty bars to nan
    set(b(iSeries),'ZData',zData);    %# Update the graphics objects
end
for k = 1:length(b)  % interpolate face color to match ice thickness
    zdata = get(b(k),'ZData');
    set(b(k),'CData',zdata);
    set(b(k),'FaceColor', 'interp');
end
view(270,90)
set(get(h,'title'),'string','Accretion Rate mm/min');  % color bar title

ylabel('Duct Temperature (C)')
xlabel('Plate Temperature (C)')
zlabel('Ice Accretion Rate (mm/min)')

figure     % repeat same process for % melt instead of duct temp
PmeltLength = round((PmeltMax-PmeltMin)/5)+1;
PlateLength = round((PlateMax-PlateMin)/0.5)+1;

BarData2 = nan(PmeltLength,PlateLength,5);
for k = 1:length(Accretion)
    ii = round(((Accretion(k,9)-PmeltMin))/5)+1;
    jj = round(((Accretion(k,3)-PlateMin))/0.5)+1;
    if isnan(BarData2(ii,jj,1))
        BarData2(ii,jj,1) = Accretion(k,5);
    elseif isnan(BarData2(ii,jj,2))
        BarData2(ii,jj,2) = Accretion(k,5);
    elseif isnan(BarData2(ii,jj,3))
        BarData2(ii,jj,3) = Accretion(k,5);
    elseif isnan(BarData2(ii,jj,4))
        BarData2(ii,jj,4) = Accretion(k,5);
    elseif isnan(BarData2(ii,jj,5))
        BarData2(ii,jj,5) = Accretion(k,5);
    end
end

for ii = 1:PmeltLength
    for jj = 1:PlateLength
        BarData_avg2(ii,jj) = nanmean(BarData2(ii,jj,:));
    end
end

b2 = bar3(PmeltMin:5:PmeltMax,BarData_avg2);
set(gca,'XTick',0:2:PlateLength)
set(gca,'XTickLabel',PlateMin-.5:1:PlateMax)
axis([0 25 -5 100])

colormap('jet')
h = colorbar;
for iSeries = 1:numel(b2)
    zData = get(b2(iSeries),'ZData');  %# Get the z data
    index = logical(kron(zData(2:6:end,2) == 0,ones(6,1)));  %# Find empty bars
    zData(index,:) = nan;                 %# Set the z data for empty bars to nan
    set(b2(iSeries),'ZData',zData);    %# Update the graphics objects
end

for k = 1:length(b2)
    zdata = get(b2(k),'ZData');
    set(b2(k),'CData',zdata);
    set(b2(k),'FaceColor', 'interp');
end
axis normal
view(270,90)
set(get(h,'title'),'string','Accretion Rate mm/min');

ylabel('% Droplet Melt')
xlabel('Plate Temperature (C)')
zlabel('Ice Accretion Rate (mm/min)')

saveas(gcf,'accretion_percent_melt.jpg')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure     %%simplified plot
plot(IceGroup(:,1),IceGroup(:,2),'o','MarkerFaceColor',[0 0 1],'MarkerEdgeColor',[0 0 0],'MarkerSize',10)
hold on
plot(WaterGroup(:,1),WaterGroup(:,2),'d','MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[0 0 0],'MarkerSize',11)
hold on
plot(ParticleGroup(:,1),ParticleGroup(:,2),'s','MarkerFaceColor',[0 1 1],'MarkerEdgeColor',[0 0 0],'MarkerSize',11)
set(gca,'XTick',0:1:25)
set(gca,'YTick',-6:1:8)
axis([0 25 -6 8])
grid on

for ww = 1:length(Accretion)
    txt = Data_Table.Case(ww);
    text(Data_Table.Duct_Temp_avg_C(ww),Data_Table.Plate_Temp_avg_C(ww)-.25,txt);
end
xlabel('Duct Temp(C)')
ylabel('Plate Temperature (C)')
legend('Ice Accretion','Water Runoff','Particle Bounce off','Location','northwest')
saveas(gcf,'accretion_simple.jpg')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure     %%simplified plot using grouped data %melt
plot(IceGroup(:,3),IceGroup(:,2),'o','MarkerFaceColor',[0 0 1],'MarkerEdgeColor',[0 0 0],'MarkerSize',10)
hold on
plot(WaterGroup(:,3),WaterGroup(:,2),'d','MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[0 0 0],'MarkerSize',11)
hold on
plot(ParticleGroup(:,3),ParticleGroup(:,2),'s','MarkerFaceColor',[0 1 1],'MarkerEdgeColor',[0 0 0],'MarkerSize',11)
set(gca,'XTick',-5:5:100)
set(gca,'YTick',-6:1:8)
axis([-5 100 -6 8])
grid on

for ww = 1:length(Accretion)
    txt = Data_Table.Case(ww);
    text(Data_Table.percent_melt(ww),Data_Table.Plate_Temp_avg_C(ww)-.25,txt);
end
xlabel('% Melt')
ylabel('Plate Temperature (C)')
legend('Ice Accretion','Water Runoff','Particle Bounce off','Location','northwest')
saveas(gcf,'accretion_simple_melt.jpg')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure %% SH plot
errorbar(Accretion(:,1),Accretion(:,11),Accretion(:,12),'o','MarkerFaceColor',[0 0 1],'
MarkerEdgeColor',[0 0 0],'MarkerSize',5)
for ww = 1:length(Accretion)
    if Accretion(:,11) ~= nan
        txt = Data_Table.Case(ww);
        text(Data_Table.Duct_Temp_avg_C(ww)+1,Data_Table.SH_mean(ww),txt);
    end
end
xlabel('Duct Temp(C)')
ylabel('SH g (H_2O) / kg (total)')
axis([0 25 0 2])
grid on
saveas(gcf,'SH.jpg')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
BarData = nan(DuctLength,PlateLength,5);  %% wetbulb temp
for k = 1:length(Accretion)
    ii = round(((Accretion(k,1)-DuctMin))/0.5)+1;
    jj = round(((Accretion(k,3)-PlateMin))/0.5)+1;
    if isnan(BarData(ii,jj,1))
        BarData(ii,jj,1) = Accretion(k,15);
    elseif isnan(BarData(ii,jj,2))
        BarData(ii,jj,2) = Accretion(k,15);
    elseif isnan(BarData(ii,jj,3))
        BarData(ii,jj,3) = Accretion(k,15);
    elseif isnan(BarData(ii,jj,4))
        BarData(ii,jj,4) = Accretion(k,15);
    elseif isnan(BarData(ii,jj,5))
        BarData(ii,jj,5) = Accretion(k,15);
    end
for ii = 1:DuctLength   %%average down to 2d  
    for jj = 1:PlateLength
        BarData_avg(ii,jj) = nanmean(BarData(ii,jj,:));
    end
end

figure
b = bar3(DuctMin:0.5:(DuctMax),BarData_avg);
set(gca,'XTick',0:2:PlateLength)    %%Fix tick marks
set(gca,'XTickLabel',PlateMin-.5:1:PlateMax)    %%replace marker lables with plate temp
axis([0 25 0 25])
colormap('jet')
h = colorbar;

for iSeries = 1:numel(b)    %%remove 0 data
    zData = get(b(iSeries),'ZData');  %# Get the z data
    index = logical(kron(zData(2:6:end,2) == 0,ones(6,1)));  %# Find empty bars
    zData(index,:) = nan;                 %# Set the z data for empty bars to nan
    set(b(iSeries),'ZData',zData);       %# Update the graphics objects
end

for k = 1:length(b)     %%interpolate face color to march ice thickness
    zdata = get(b(k),'ZData');
    set(b(k),'CData',zdata);
    set(b(k),'FaceColor', 'interp');
end
view(270,90)
set(get(h,'title'),'string','Wet Bulb Temperature (C)');   %% color bar title

ylabel('Duct Temperature (C)')
xlabel('Plate Temperature (C)')
zlabel('Wet Bulb Temperature (C)')

cd('Z:\AERTS Test Data\Particles Wind Tunnel')
saveas(gcf,'wetbulb temp.jpg')

figure
errorbar(Accretion(:,1),Accretion(:,15),Accretion(:,16),'o','MarkerFaceColor' 
,[0 0 1],'MarkerEdgeColor',[0 0 0],'MarkerSize',5)
xlabel('Duct Temp (C)')
ylabel('Wetbulb Temperature (C)')
axis([0 25 0 10])
grid on
saveas(gcf,'wetbulb2.jpg')
VITA

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