CALIBRATION OF ICE WATER CONTENT IN A WIND TUNNEL / ENGINE TEST CELL FACILITY

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1. INTRODUCTION

In recent years, aviation sector interest in the measurement of cloud ice particle total mass and mass distribution has grown due to an increasing number of in-service single and multiple jet engine power-loss events on commercial aircraft usually when flying in the vicinity of deep convection (Lawson et al. 1998, Mason et al. 2006, Pasztor, 2008). Pilot reports, flight data recorder data, and some industry flight test data strongly indicate that the events are probably related to the ingestion of high ice water content into the engines. Such events have obvious cost and safety implications to the industry and the public. Recently, the National Research Council of Canada (NRC) has been working to create an ice particle simulation facility for testing jet engine and/or engine components in high ice water content (IWC) conditions. Ice particles are created by shaving ice blocks, or by using a grinding mill. Environment Canada is collaborating with NRC on the calibration of the IWC quantities produced in the tunnel. By measuring the relative profile of IWC across the tunnel, and knowing the amount of ice delivered into the tunnel, it is possible to provide an absolute estimate of the tunnel IWC at any location across the tunnel.

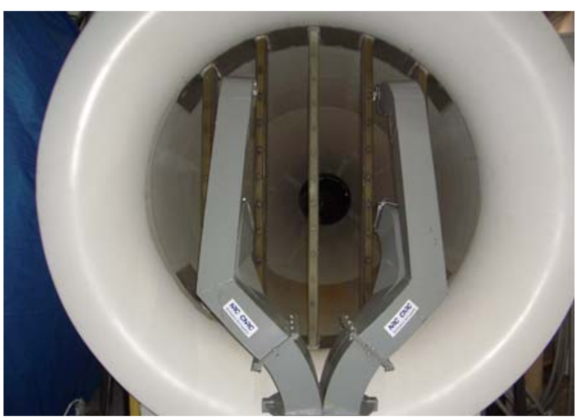
The obvious application of this work to the cloud physics community is as a first step towards the 'absolute' calibration of in-situ airborne IWC sensors. Estimates of cloud ice water content (IWC) by airborne in-situ sensors have to date not been convincingly validated. Accuracy assessments have usually been attempted only through estimates of contributing errors, or through comparisons of instruments with different operating principles. In the case of cloud liquid water content measurements, absolute accuracy estimates of airborne sensors have been possible by comparison to icing cylinder and blade measurements in icing wind tunnels, where the errors in the latter measurements are relatively small and can be quantified (e.g. Strapp et al. 1982, King et al. 1985 , Strapp et al. 2002). No equivalent 'absolute' comparison standard has been available for IWC measurement systems. Airborne IWC instrument comparisons have tended to reveal relatively large discrepancies, and researchers have been reluctant to quote absolute accuracies.

This paper will describe an 'absolute' calibration of IWC in an engine test facility, where the emphasis has been on the creation of very high IWC conditions at relatively high velocities. The facility will ultimately also be used to evaluate current instrumentation and develop new instrumentation for the in-situ measurement of high IWC, to support future airborne cloud measurements planned in high IWC regions of deep tropical convection for engine power-loss studies.

2. THE TEST FACILITY AND TEST MATRIX

The National Research Council Gas Turbine Laboratory has several engine test cells used for testing of jet engines up to approximately 25,000 lbs thrust. The one used for this test is an open circuit tunnel that takes in air from outside the facility building into the test cell, and exhausts it outside the facility building. The disadvantage of this type of tunnel over a closed-loop tunnel is that it can only be operated when outside air temperatures are colder than about -10C in order to avoid melting and sticking of the ice particles in the delivery system. The very large advantage of the system however is that there is no recirculation of ice particles as has been observed in closed circuit tunnel. This is fundamentally important in the estimate of the absolute IWC by simply accounting for how much was shaved and into what volume it was injected. The NRC first developed this capability for ingesting ice particles into engines in the 1950s. The ice shaving device they developed consists of a rotating drum with teeth that rip at the surface of ice blocks that are pushed into the drum. Ice particles that are shaved off the block by this process fall into a chute and are blown into a duct towards the entrance of the tunnel by a 25 HP blower. The main chute divides into 4 smaller ducts that then eject the shaved ice into 4 quadrants at the inlet of the circular cross section that constricts to a 34.5 inch (87.6 cm) test section (Fig. 1). The maximum tunnel speed is approximately 160 ms^{-1}, depending on the amount of equipment in the test section.

Figure 1. Picture of entrance into the open circuit engine test cell/wind tunnel, with 4 ice-injection ducts (dark grey coloured) providing ice particles from the ice shaver, and water spray bars in behind (unused for this study). The diameter of the test section is ~88 cm.



Shaver Rate (cm/min)	**Tunnel speed ms^{-1}**	**Fully Mixed IWC (gm^{-3})**	**Comments**
10.2	150	0.59	mapped
17.8	150	1.03	mapped
25.4	150	1.47	mapped
38.1	150	2.20	mapped
50.8	150	2.93	mapped
76.2	150	4.40	impractical to map
25.4	80	2.76	Comparison pt. to Cox & Co. tunnel, mapped

Table 1: IWC Test Matrix for NRC Test Cell Ice Simulation

Industry airborne studies in the 1950s measured IWC concentrations in deep tropical convection up to about 8.0 gm-3 (McNaughtan, 1959). Given that IWC values in deep adiabatic cores could at least in theory reach values in excess of 9 gm-3 (Mazzawy and Strapp, 2007), an industry-government working group concluded that 10 gm^{-3} would be a good preliminary design upper limit to adopt while implementing various parts of the technical plan addressing the engine power-loss issue. Therefore, a test matrix was developed that could be used to produce calibrated levels of IWC, with the hope of reaching 10 gm^{-3} at 150 ms^{-1} (Table 1). The actual test matrix spans the practical limits imposed by the ice shaver system. On the low IWC side, stable center-position IWC values could not be obtained. At the highest shaver rates, the time it takes to fully shave one ice block drops below 1.5 minutes, insufficient for stabilization and mapping of the tunnel. Therefore the practical lower and upper limits for the determination of the absolute calibration were for the 10.1 to 50.8 cm/min shaver rates, corresponding to 0.59 to 2.93 gm^{-3} if the ice were evenly distributed through the tunnel. Although this falls short of the initial target of 10 gm^{-3}, it was concluded that additional mass could be added in future years by adding an additional shaver or other ice producing device. Furthermore, it was expected that the IWC values of the 76.2 and

Shaver Rate (cm/min)	Fully mixed IWC	Est. Median Mass Dia (μm)
5.1	0.59	197
10.2		218
25.4	1.47	228
50.8	2.93	267

Table 2: Estimates of median mass diameter of ice particles from 2DCgrey images, taken at 80 ms^{-1}

106.7 cm/min points could be determined by extrapolation of the other lower shaver rate points, and used for special short experiments increasing the fully-mixed IWC values to about 6 gm^{-3}.

Ice slide and visual impressions of the plume of ice particles produced by the shaver suggests that the median mass diameter of the particles can be varied substantially by changing the drum rotation speed and 'wobble' of the cutting teeth. Due to lack of time, the size varying capabilities of the shaver have not been characterized. Rather, it was decided to always run the same rotation and wobble speeds so as to produce what was thought to be the smallest ice particles, to hopefully simulate the small particle sizes observed near cores of thunderstorms. A 15 micron resolution Particle Measuring Systems 2DC-grey cloud imaging particle spectrometer was used to measure the particle spectra and estimate the median mass diameters (MMD) at the different shaver rates. It was necessary to perform these tests at 80 ms^{-1} rather than 150 ms^{-1} because the probe repeatedly failed at high airspeeds and high IWCs, possibly due to effects caused by the high electrostatic charging by the ice particle impacts on the probe. This type of failure has also been observed with similar particle spectrometer probes during industry flight testing in high IWC regions near thunderstorm cores. Results of the testing at shaver rates of 5.1, 10.2, 25.4, and 50.8 cm/min are shown in Table 2. Sample 2DC-grey images from the 25.4 cm/min run are given in Fig. 2, and a normalized mass distribution for the 25.4 cm/min run is shown in Fig. 3. Although these MMD results cannot be considered highly accurate because the measurements below 100 μm are known to have limited accuracy (e.g. Korolev et al. 1998, Strapp et al. 2001), they do provide a first approximation, and probably an upper limit to the median mass diameters of the ice particles in the tunnel for this shaver configuration. The estimated MMDs are found to increase from about 200 to 270 μm with increasing shaver rate (IWC). The values are similar to those reported for the Cox and Co. Icing Wind Tunnel for their shaved ice clouds (Emery et al. 2004).

Figure 2: Sample 2DCgrey images from the 25.4 cm/min ice shaver run at 80 ms^{-1}. The images with green circumscribed boxes are accepted by the 2D analysis software. The height of the box is 960 μm

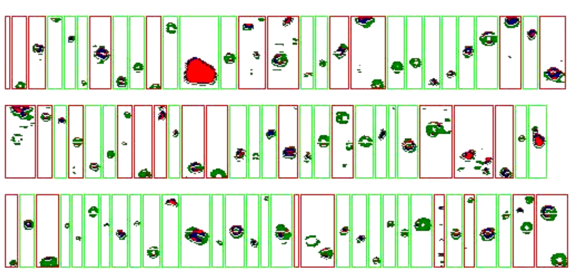
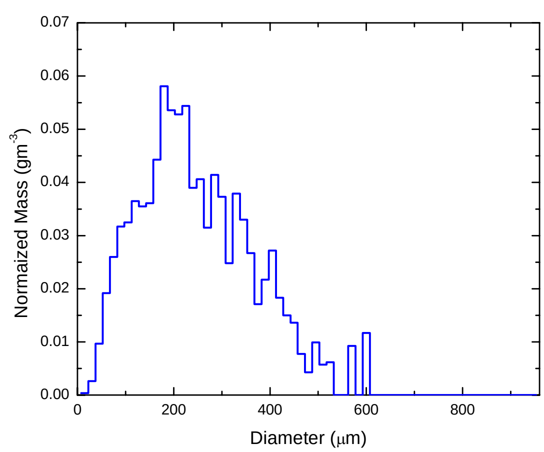


Figure 3: Mass distribution for 25.4 cm/min ice shaver run at 80 ms^{-1}. Data are from a PMS 2DCgrey cloud particle spectrometer.



3. INSTRUMENTATION AND TEST METHOD

For a given shaver rate, assuming that conditions are reproducible to an acceptable level, the absolute IWC at any location in the tunnel can be determined by mapping the tunnel with a probe that measures IWC, producing isopleths of relative IWC across the tunnel, and then by scaling the isopleths of IWC so that they produce the known flux of ice that is being injected into the tunnel by the shaver. One necessary requirement is that the IWC probe must measure a constant fraction of IWC; it does not matter if the fraction is close to unity although that is of course preferable. An end result of a series of calibrations at different shaver rates is that the probe itself is calibrated, and its linearity with IWC is thereby determined. Another necessary condition is that all of the ice particles are deposited into the tunnel, and do not build up in the ducting or shaver. Normally, this did not occur as long as the outside air temperature was colder than -10 C, and the ducting was frequently inspected for confirmation. Finally, there must be no melting and evaporating of the ice by the shaving drum. A simple experiment was performed by catching all of the ice particle shaved by the rotating drum, and a comparison to the calculated mass based on the loss of volume of the shaved block revealed a loss of less than 3%.

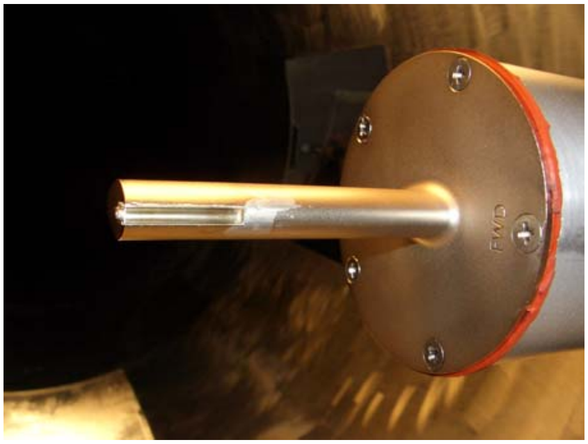
The isopleths of relative IWC in the tunnel were determined by mapping the tunnel with vertical traverses with the IWC probe at 3 inch (7.62 cm) intervals with a vertical movement of about 50 cm/minute. Traverses at each horizontal map location were repeated three times to establish variability and to provide a more representative average.

Following experience on an industry test aircraft program (Strapp et al, 1999), it was recognized that there was probably no airborne total water content system that could perform adequately in the high-speed/high IWC environment. In response, a Science Engineering Associates (SEA) hot wire total

Figure 4. Picture of the early SEA TWC sensor design used in 2007 testing. This sensor was used successfully at 100 ms^{-1}. but was bent and damaged at 150 ms^{-1} in high IWC values. The sense element is a solid-wire, 2 mm deep half-cylinder

water content system was specially modified to provide sufficient power to measure the expected high IWC values. Furthermore, it was felt that the solid wire of the early version of the SEA sensor available at the time (a 2 mm deep half cylinder) would be more resistant to the destructive effects of the particle impacts at these higher speeds than other wound-wire alternatives. Although this early sensor has been used successfully in Environment Canada/NRC airborne studies on the NRC Convair 580 at 100 ms^{-1} for several years, the ice particle impacts in the tunnel at the higher airspeed did indeed eventually bend the sensor in the center of the sample tube and break the connection to the sample tube at the top of the sensor. A picture of the damage to the sensor head used in the winter of 2007 is shown in Fig. 2. In fact, when the higher IWC values were sampled, these sensors were damaged very rapidly, resulting in the early cancellation of the tunnel testing in 2007. It is data from this first season that will be provided in the next section, from a shaver rate that did not result in destruction of the sensor. It was however concluded that a newer more robust sensor would need to replace the standard sensor the following winter. The new sensor developed for the winter of 2008 by SEA is

Figure 5. Picture of new robust TWC sensor designed by Science Engineering Associates for high-speed/high IWC operation. This sensor was operated successfully in winter 2008 testing at 150 ms^{-1} and IWC estimated to be in excess of 8 gm^{-3}. The same sense element as in the 2007 model is used, but was imbedded in a leading edge.



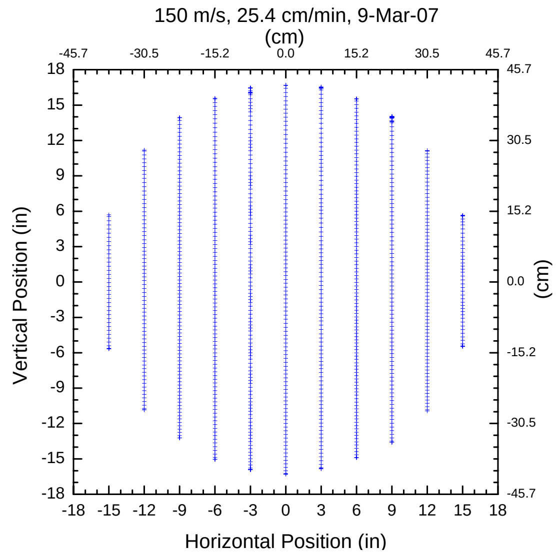
shown in Fig. 5. This sensor incorporates the same sold wire and catch geometry as the early SEA TWC sensor, but it is imbedded into the leading edge of a 12 mm wide strut. This sensor was successfully tested in December 2007, and performed without any discernible damage or measurement corruption throughout the mapping of the test matrix completed in January and February of 2008. It has been exposed to estimated IWC values in excess of 8 gm^{-3} at 150 ms^{-1} without any indication of damage or saturation.

4. 2007 RESULTS.

This section will describe the results of the 2007 calibration of the NRC engine test cell calibration for IWC for the 25.4 cm/minute shaver rate case, using an early version of the SEA TWC sensor shown in Fig.4.

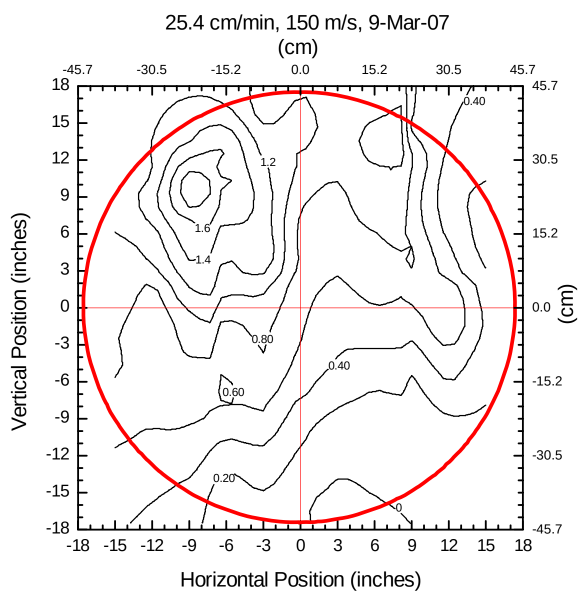
The TWC sensor was mounted on a traversing arm that could be manually adjusted for horizontal position, and was motor-driven in the vertical position. The procedure to map the tunnel concentrations is best illustrated with an example (Fig. 6). The horizontal position of the probe was stepped at 7.6 cm intervals. At each interval the TWC

Figure 6: Illustration of raw data collection points during vertical traverses of tunnel, used to create isopleths of IWC for a given ice shaver setting



instrument traversed vertically at about 50 cm/min. The points shown in small print on Fig. 6 represent the positions at which centered 10 s average TWC values were calculated. Next, data from three complete mappings as in Fig. 6 for the same setting were averaged to give a final smoothed

Figure. 7. Isopleths of IWC as measured by the early version of the SEA TWC sensor (Fig. 4).



representation of the TWC distribution in the tunnel. The isopleths of IWC, as measured by the SEA sensor, are given in Fig. 7. Note that the measured IWC at the center of the tunnel, the prime measurement location, is approximately 0.65 gm^{-3}, but there is a concentrated maximum of in excess of 1.8 gm^{-3} in the top-left quadrant of the diagram. Fig. 7 shows the isopleths of IWC as viewed looking upstream in the tunnel, so when compared to the photograph looking down the tunnel in Fig. 1, the right and left quadrants must be flipped. The offset maximum is then easily explained. The bends in the ducting result in the top-right duct shown in Fig. 1 being the one with the most direct route for the ice particles. Centrifugal forces due to the bends direct the ice particles more favourably to this duct.

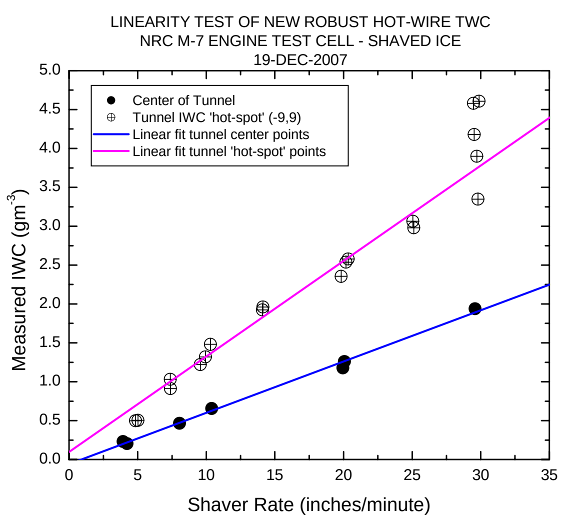
The final step in the calibration is the comparison of the estimated measured total mass flux down the tunnel to the estimated true mass flux. The true mass flux is estimated from the volume of ice shaved per unit time based on the shaver rate and the cross sectional area of the ice blocks, the density of the ice blocks, and the airspeed in the tunnel. The ice blocks used in these tests are commercially produced in such a way as to minimize the number of air bubbles, and are commonly used for ice sculptures. The density of the ice was estimated by the block weight and volume to be approximately 0.92 gcm^{-3}. At 25.4 cm/min, the 348 cm^2 blocks inject approximately 25.4x348x0.92 g of ice into the tunnel (8132 g) per minute, or 135.5 g/s. One of the intermediate products used to produce the isopleth diagram of Fig. 7 is an estimated 1 cm x 1 cm IWC matrix, which can be used to calculate the flux of ice through each 1 cm x 1 cm square by multiplying the IWC matrix value by the tunnel velocity. When these fluxes, based on the instrument response, are added up to give the total instrument-based flux through the tunnel cross-section, the value obtained for this setting is 68.2 g/s. Therefore, the efficiency of the sensor is 68.2/135.5, or approximately 0.50. The instrument reads approximately a factor of 2 low. These results are not unexpected, and qualitatively agree with past wind tunnel data collected at the Cox and Co. Icing Wind Tunnel, also using an ice shaver to create ice particle clouds. Emery et al. (2004) and Strapp et al. (2005) have provided evidence from high speed video records of ice particles being ejected from the capture area of hot-wire TWC sensors, and pooling of the Nevzorov TWC sensor in high IWC conditions. Although the results are confounded by ice particle recirculation, Strapp et al. (2005) also showed that the deepest sensor tested (16 mm) showed the least mass ejected from the capture volume, and its response of was at least a factor of 2 larger than the lowest reading shallow sensor (2 mm). Emery et al. (2004) also showed that a variety of hot wire devices responded within about 25% in liquid conditions at ~20 μm MVD, indicating that the difference in hot wire response in ice particle conditions was not due to electronics. Isaac et al. (2006) have also observed with high-speed video the breakup and ejection of some of the mass of natural dendrites striking the cone of the Nevzorov probe, indicating that underestimates of ice mass may also be expected in natural clouds.

5. 2008 RESULTS.

After limited measurements in 2007, measurements were resumed in the winter of 2008 with the newly designed robust hot-wire TWC probe (Fig. 5). A full set of mappings of the tunnel at all of the ice shaver settings listed in Table 1 was accomplished, with the exception of the highest setting that was deemed impractical to map due to short ice block shaving times (see section 2). The analysis of these results into tunnel profiles and absolute calibration points for the new robust sensor is ongoing, and could not be completed in time for this report.

In addition to the tunnel mapping, a series of runs were performed at the center of the tunnel to provide some data to support the linearity of the new robust probe’s response with IWC. The geometry of the new sensor is very similar to the early sensor (Fig. 4), in that the sensing elements are 4 mm half-cylinders with a depth of 2 mm in each case. Since the response of the older probe was found to be linear with the rate of injection of ice into the tunnel (Strapp et al. 2005), it was hoped that the same would be true for the new probe. Fig. 8 displays the response of the new probe as a function of ice shaver rate for two locations in the tunnel, the center and near the 'hot-spot' (maximum) located in Fig. 7. Note that at both locations, the response of the probe is indeed linear with respect to the rate at which ice is delivered to the tunnel. The values in Fig. 8 are averages varying between about 1-3 minutes, the time decreasing with increasing shaver rate. The repeatability of the results is quite good, with the exception of the highest shaver rate, where the short averaging interval and the evidently reduced shaver stability result in noticeably higher variability. Note that the results of Fig. 8 are encouraging, since the absolute calibration method requires that the mapping device measure linearly with respect to IWC. The final verification of the method will be the probe efficiencies, determined as in the case of the tunnel mapping example summarized in section 4. If the efficiencies

Figure. 8: Response of the new robust hot-wire TWC sensor as a function of delivery rate of ice particles to tunnel. Results are shown for the center of the tunnel, and a location near the tunnel 'hot-spot'.



remain relatively constant with increasing IWC, this basic linearity requirement will be confirmed.

The similarity of the new sensor to the old sensor also suggests that the response of the sensors might be similar for the same shaver rate. The IWC at the center position of Fig. 7, estimated at about 0.65 gm^{-3} for the early sensor, compares very favourably to the new sensor. The best fit line for the center position in Fig. 8 indicates an IWC of ~0.60 gm^{-3}. This implies that the efficiency of the new probe may also be of the order of 50%.

6. SHAVED ICE VERSUS NATURAL ICE

The main focus of this work is to create a calibrated ice cloud simulation in the NRC M-7 test cell that can be used in the short-term for qualification of existing IWC and other airborne probes in the high speed, high IWC environment, for the development of new instrumentation, and for physical testing of engine components to help answer how ice particles cause ice accretion in a jet engine. Although there is no doubt that the shaved-ice simulation cannot duplicate natural ice crystal morphology, in particular the large complex and often delicate particles seen in nature, it is vital that existing resources be developed on a time scale of less than 2-3 years that can realistically meet the target IWC values thought to be required to induce engine power-loss events. Since the median mass diameter of the ice clouds that induce power-loss events is thought to be perhaps less than 200 μm or so, it is suggested that shaved ice may be a reasonable facsimile for the majority of the natural ice particle spectra, given that large particles are unlikely to remain intact any appreciable distance into the engine. The simulation of calibrated IWC mass concentrations is highly important in providing first-order confidence that heat-transfer conditions thought to be critical to engine icing are realistic.

Probes that are qualified and calibrated in the M-7 test cell will ultimately be used as part of an industry technical plan to characterize the high IWC environment in a focused field program. The instrument calibrations derived from the shaved ice simulations will somehow need to be tested in natural clouds. It is anticipated that this will be accomplished by comparison of the relationships between various IWC measurement probes in the tunnel versus in natural clouds. Other special airborne experiments, such as the further use of high speed video of probe sensing elements, may be also pursued. IWC measurement devices must be able to accurately operate in both simulated ice conditions and natural ice conditions. The calibration in simulated ice conditions moves us one step forward towards this goal.

7. FUTURE PLANS

The analysis of the 2008 calibration data for the 5 ice shaver rates shown in Table 1 will be completed shortly, in a manner similar to that described in section 4. This will provide a tunnel with estimated IWC at the center varying between approximately 0.5 and 3.6 gm^{-3}, and at a tunnel hot-spot for special experiments between approximately 1.5 and 11 gm^{-3}. This will also provide an 'absolute' calibration of the robust hot-wire TWC sensor within this IWC range. Once completed, a series of calibrations are planned for the DMT Counter Flow Virtual Impactor, the Nevzorov and possibly other hot-wire devices. A new isokinetic total water content measuring device targeting up to 10 gm^{-3} at 150 ms^{-1} is also being developed by NRC and EC for this project, and if successful its comparison to the tunnel values will help substantiate the calibrations using the robust sensor. A variety of further instrument testing experiments are planned to check the performance of pitots, temperature probes, and wind/gust measuring devices in the high IWC environment. The tunnel will also be used for experiments using model engine components to investigate the engine icing problem.

8. SUMMARY

An ice-cloud simulation in an open-circuit wind tunnel/engine test cell has been documented in an attempt to provide an absolute calibration of IWC. This work has been motivated by a growing number of jet engine power-loss events thought to occur in high IWC clouds. Absolute calibration of IWC at a velocity of 150 ms^{-1} has been accomplished by measuring the total amount of ice injected into the tunnel, mapping with a hot-wire probe the spatial distribution of the ice in the tunnel, and then performing a mass-closure calculation. A full example for one ice shaver rate was given, which provided a map of the estimated absolute IWC at all locations across the tunnel sample section. This calibration also revealed that the mapping probe measured about 50% of the true IWC. A full set of 5 ice shaver rates, expected to provide IWC values near the center of the tunnel between 0.5 and 3.6 gm^{-3}, and near a 'hot-spot' in the tunnel of between 1.5 and approximately 11 gm^{-3} have now been measured, and will be analysed over the next several months.

Measurement of the high IWC environment at high speed has been found here and by others to be very challenging. An early hot-wire probe used in 2007 for the tunnel mapping failed repeatedly at the higher IWC values due to the destructive nature of the particle impacts. A new robust version of the probe was developed in 2008, which performed without problems throughout the range of IWC values. A necessary condition for the absolute calibration method is that the probe used to map the spatial distributions has a linear response with respect to IWC. Data collected in 2008 do indeed suggest that the robust probe has a linear response to IWC.

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