Validation of a Compact Isokinetic Total Water Content Probe for Wind Tunnel Characterization at NASA Glenn Icing Research Tunnel and at NRC Ice Crystal Tunnel

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A new compact isokinetic probe to measure total water content in a wind tunnel environment has been developed. The probe has been previously tested under altitude conditions. This paper presents a validation of the probe under a range of liquid water conditions at sea level in the NASA Glenn Icing Research Tunnel and with ice crystals at sea level at the NRC wind tunnel. The compact isokinetic probe is compared to tunnel calibrations, hot wire probe and a flight version of the isokinetic probe.

Nomenclature

A	=	area (m^2)
AOA	=	angle of attack (degrees)
F	=	feed rate (cm/s)
I	=	ice ingestion rate (g/s)
IKF	=	isokinetic factor
IKP	=	isokinetic total water content probe
IWC	=	ice water content (g/m^3)
LWC	=	liquid water content (g/m^3)
MVD	=	mean volume diameter (μm)
MW	=	multi-wire probe
$\dot{m}$	=	mass flow (kg/s)
p	=	pressure (kPa)
ρ	=	density (kg/m^3)
T	=	temperature (°C)
TWC	=	total water content (liquid and ice) (g/m^3)
V	=	speed (m/s)
ω	=	specific humidity ($g_{water}/kg_{dry\ air}$)

Subscripts

corr	=	corrected for air speed
inlet	=	at the inlet to the IKP
meas	=	measured
nom	=	nominal air speed (150 or 80 m/s)
o	=	total or stagnation conditions (no subscript implies static conditions)
∞	=	freestream conditions

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I. Introduction

The current state of the art for measuring total water content (TWC) in high altitude, glaciated or mixed phase aircraft icing environments uses an isokinetic probe (IKP) to sample the atmosphere. The development of this technology was necessary to overcome inaccuracies associated with hot wire TWC probes as they are designed for traditional super cooled liquid water icing and can significantly underestimate the TWC in an ice crystal icing (ICI) environment. The original flight IKP was developed by the National Research Council Canada (NRC) in cooperation with Environment Canada (EC) with contributions from Science Engineering Associates, Inc. (SEA). This probe was developed to be utilized on flight test aircraft to measure TWC in the atmosphere as reported in previous papers[1-5]. In 2013, SEA, with NRC as a partner, led a NASA-contracted effort to downsize the original flight IKP so it could be used on the Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE) Falcon 20 aircraft.[6]. This downsized flight IKP is referred to as the IKP2 in this paper. The IKP2 has been extensively ground tested in supercooled liquid and high concentrations of ice crystals and was successfully used in three flight campaigns to measure TWC in deep convective ICI environments at high altitude.

The need for this capability to ensure accurate inflight atmospheric TWC measurements also exists for icing wind tunnels (IWT) that reproduce ICI environments. Therefore, NRC developed an IKP with a compact sampling head shown in Figure 1 and is referred to as the compact IKP (CIKP). The sampling head is mounted in the tunnel flow and is traversable throughout the cross-section with the other components of the CIKP system located remotely, outside of the tunnel. This new system is based on the existing IKP2 flow path technology developed by NRC and is intended for operation in wind tunnels at flight representative pressures, temperatures and Mach numbers. It also has an extended TWC range compared to the flight versions as tunnels are often required to exceed values of TWC seen in the atmosphere, often by a factor of 2 or more to account for the concentration that occurs around the aircraft. In addition to being useable in tunnels, the compact size also allows for simpler installation on aircraft where there is insufficient structure or space to support the larger flight IKP versions, an example of which are flight test aircraft having only window penetrations for probe mounting.

Although the impetus for this technology came from the need to measure TWC in an ICI environment, this technology will also measure TWC in a liquid water environment such as traditional super cooled liquid water icing and is an ideal technology for super cooled large droplet (SLD) icing, another application where hot wire probes can have difficulty obtaining accurate measurements. In 2014 the probe was functionally checked and validated in NRC's Research Altitude Test Facility in its ice crystal configuration[7]. Subsequently, the probe was tested in sea level facilities. Liquid water testing was performed at the NASA Glenn Icing Research Tunnel (IRT) and ice crystal testing at the National Research Council Canada (NRC) ice crystal tunnel in building M7.
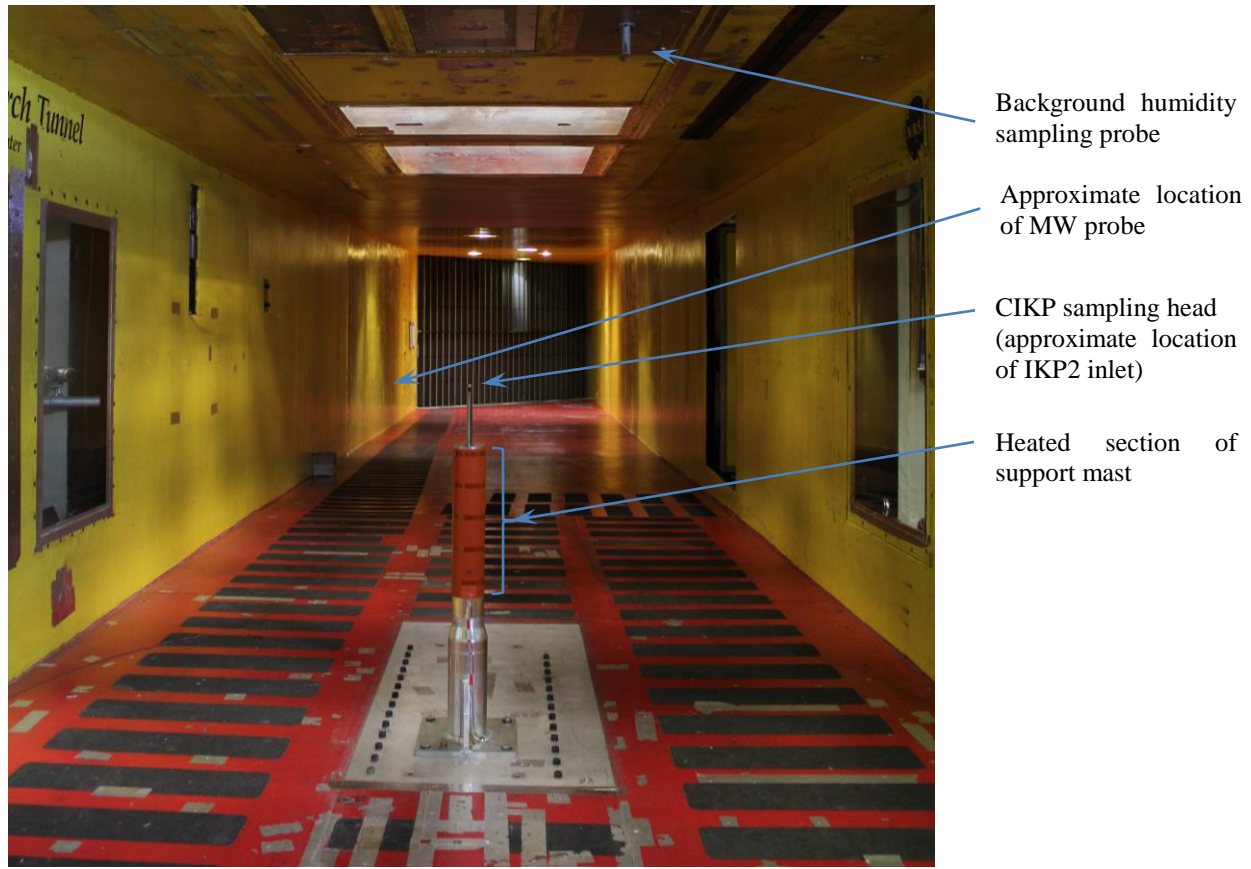
Figure 1. Compact isokinetic probe sampling head

II. Super Cooled Liquid Water testing

The compact IKP was tested at the NASA IRT in October 2015. Following two days of testing, the CIKP was replaced with the IKP2 owned by NASA[6]. The intention of testing with the IKP2 was to confirm the test conditions for the compact IKP. The test program covered a range of tunnel calibration liquid water contents (LWC) from 0.5 to 4 g/m³, median volume diameters (MVD) from 15 to 266 μm, and airspeeds from 51 to 154 m/s. The total temperature and pressure was maintained near -10℃ and near sea level pressure. The compact IKP was also tested at a range of isokinetic factors (IKF) to determine the effect of off-design operation on the results.

A. Experimental Set Up

The CIKP was mounted on the tunnel floor with the inlet 0.91 m (36 inches) from the floor and 1.37 m (54 inches) from the starboard wall (the starboard wall is the south wall or the pilot eye view left wall). The CIKP is shown installed in the IRT prior to testing in Figure 2. The upper 0.36 m (14 inches) of the CIKP support mast was heated to prevent ice accretion. The background humidity probe is also shown and is installed 0.97 m (38 inches) from the port wall with the inlet approximately 6.4 cm (2.5) from the top wall.

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Background humidity sampling probe

Approximate location of MW probe

CIKP sampling head (approximate location of IKP2 inlet)

Heated section of support mast

Figure 2. CIKP installed in IRT

A Science Engineering Associates (SEA) multi-wire probe (MW) was also installed concurrently with the CIKP to provide a real-time diagnostic measurement of the IRT cloud conditions. The MW was located at 0.91 m (36 inches) from the ceiling and 0.99 m (39 inches) from the starboard wall. The MW was approximately 0.38 m (15 inches) lateral offset from the CIKP. The spatial discrepancy means that a direct comparison of the MW and the IKP was not possible but the IRT calibration indicates that the LWC difference should be less than 10%. The MW results were corrected using the procedure developed by Rigby et al.[8] to account for the collection efficiency of the MW probe. No attempt was made to correct the MW result for the difference in LWC at its location and the center.

After the CIKP testing was completed, it was removed and the IKP2 was installed. The IKP2 was installed with the inlet near the tunnel centerline (1.37 m (54 inches) from the port wall and 0.92 m (36.3 inches) from the floor). This is within 0.75 cm (0.3 inch) of the location of the CIKP inlet. The MW probe remained in the same position as with the CIKP testing.
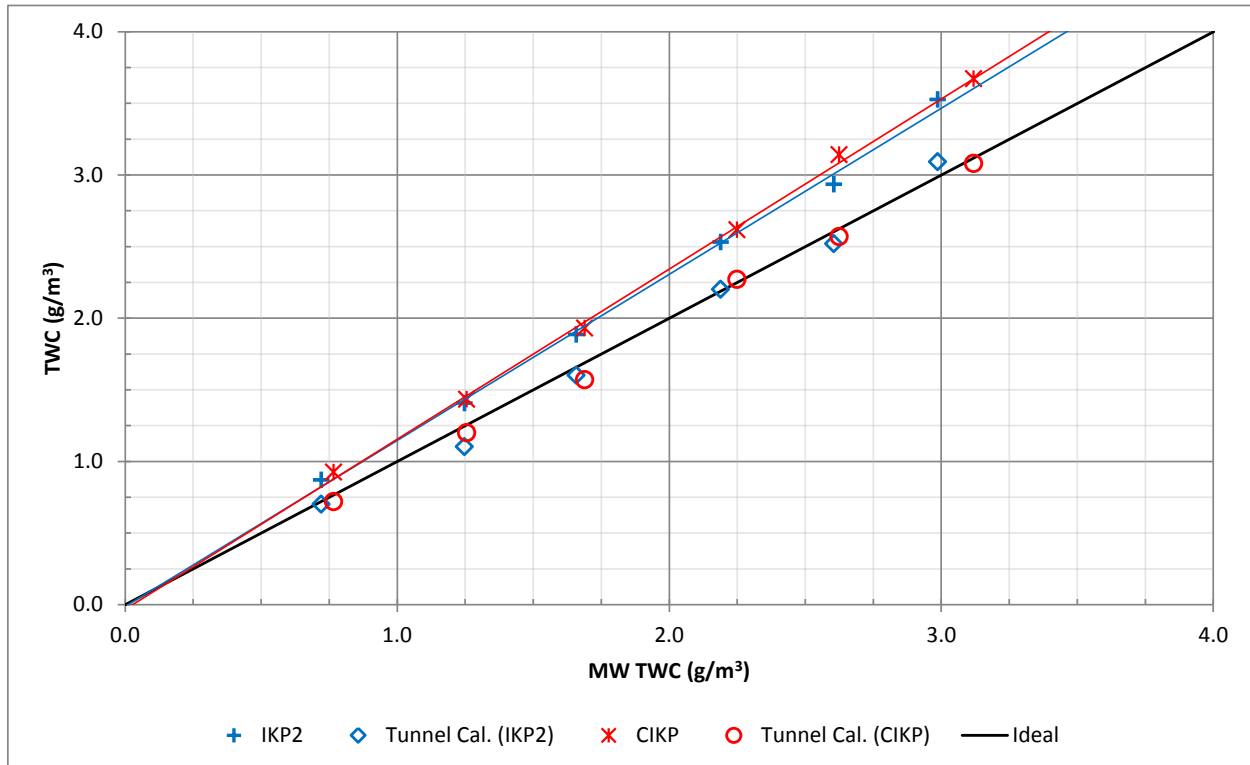
B. Results

LWC sweeps were performed at air speeds of 51, 77 and 103 m/s. The most comprehensive was performed at 77 m/s and the results are presented in Figure 3. This differs from the data presented by Strapp et al.[6] who examined the IKP TWC relative to the tunnel values. The objective was to compare the CIKP to the IKP2 so the results were examined relative to the MW. Since the CIKP and IKP2 were tested at different times the MW would capture any random variations in the tunnel behavior. Therefore, the TWC for the CIKP and IKP2 are plotted against the TWC from the MW. The tunnel LWCs, as reported by the IRT data system, are also presented for comparison. The LWC reported by the IRT data system is based on the 2015 tunnel calibrations and the real time measurement of nozzle and tunnel conditions.

The ideal line is where the MW TWC matches the TWC on the y-axis. As expected, the tunnel TWCs closely match the MW, since the tunnel calibration used the MW probe[9]. As the CIKP and the IKP2 were tested on separate days there is a corresponding set of tunnel LWC for each instrument. The CIKP and the IKP2 match each other very closely but are significantly higher than the MW and tunnel values. Figure 4 and Figure 5 present the data for

the LWC sweeps at 51 and 103 m/s. The data sets are smaller than at 77 m/s but the results are similar. The CIKP and IKP2 match very closely but are larger than the tunnel calibration values. The linear coefficients for the least squares fits are given in Table 1 with the 95% confidence intervals. The confidence intervals for the 51 and 103 m/s data sets are large due to the small sample size. The ideal line where the probe TWC matches the tunnel TWC would have a slope of 1 and a y-intercept of 0. If the probe differs from the tunnel by a constant ratio the y-intercept should be 0 regardless of the slope. If the least intercept is not 0 it indicates that the probe has an offset error or the ratio of the probe TWC to the tunnel is not consistent. This could be caused by saturation of the probe at higher TWCs. As the water builds up in the probe it reduces the amount measured and changes the ratio of measured TWCs. The least squares fit to both IKP data sets almost pass through (0,0), as expected, with the 95% CI on the y-intercept including 0 with a wide margin.

Table 1. Least squares coefficients with 95% confidence intervals for LWC sweeps for IKP measured TWC versus MW measured TWC

Air Speed (m/s)	Probe	Slope		y-intercept	
		Coefficient	95% CI	Coefficient	95% CI
51	CIKP	1.19	1.30 1.08	0.04	0.34 -0.25
	IKP2	1.14	1.43 0.93	0.12	0.87 -0.70
77	CIKP	1.19	1.25 1.12	-0.03	0.10 -0.17
	IKP2	1.16	1.25 1.07	-0.01	0.17 -0.19
103	CIKP	1.14	1.20 1.09	-0.01	0.06 -0.07
	IKP2	1.20	1.77 0.62	-0.19	1.08 -1.46

Figure 3. TWC results under liquid water conditions at T_o=-10°C, p_o=100 kPa, V=77 m/s and nominal MVD=22 μm with least squares fit lines for IKP results

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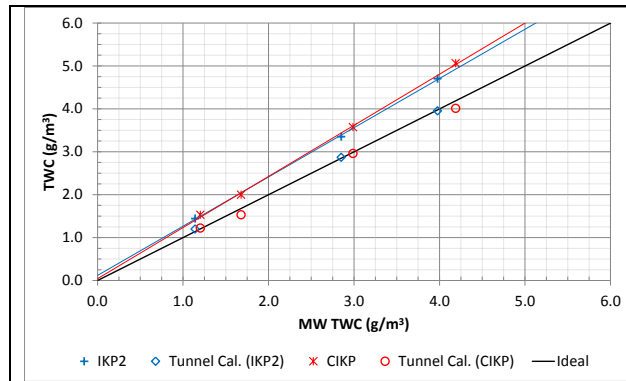
Figure 4. TWC results under liquid water conditions at T_o=-10°C, p_o=100 kPa, V=51 m/s and nominal MVD=22 µm with least squares fit lines for IKP results
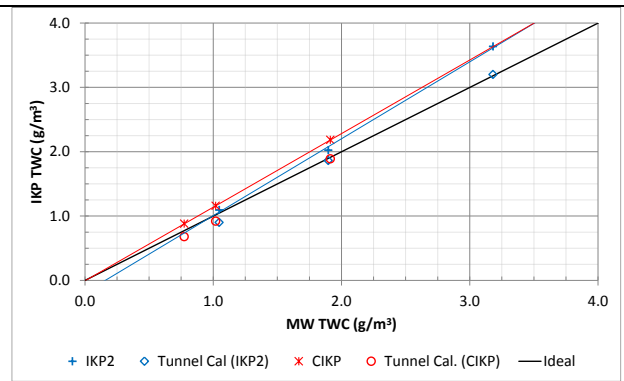
Figure 5. TWC results under liquid water conditions at T_o=-10°C, p_o=100 kPa, V=103 m/s and nominal MVD=23 µm with least squares fit lines for IKP results

Two MVD sweeps were performed at 77 m/s and 103 m/s. The results at 77 m/s are presented in Figure 6 for the CIKP inlet at a 0° angle of attack (AOA) and a 15° AOA. The TWC at 15° AOA was corrected to account for the reduced area perpendicular to the flow by dividing by the cosine of 15°. This was to determine the error due to changes in flow at the inlet rather than the obvious error due to a smaller collection area. The uncorrected values fall significantly below the 0° AOA. The corrected values match closely, but generally fall slightly below the 0° AOA, indicating that the distorted flow around the inlet is causing a reduction in the collection efficiency. If the probe is operated with a significant AOA then the dominate error is that due to the reduced collection area. There does not appear to be any consistent trend with respect to MVD in the CIKP response compared to the MW.

A 0° AOA MVD sweep was also performed at 103 m/s and the results plotted versus Stokes number in Figure 7. Stokes number was chosen as the independent variable because it is related to the probe collection efficiency and the geometry of the probe was constant as all tests were at 0° AOA. The smaller the Stokes number the more closely the particles follow the streamlines. The Stokes number was calculated identically to Davison et al.[10]. A value of one falls between the particles following the streamlines and entering the probe regardless of the air flow.

The CIKP, IKP2 and tunnel all show an increasing trend with increasing Stokes number. Both the IKPs and the tunnel calibrations all show similar increasing trends with Stokes number which may indicate that it has something to do with the MW probe measurement. Possibly the distribution in the tunnel is changing with the Stokes number resulting in a different reading at the MW location since the IKPs and tunnel calibrations are all nominally at the center while the MW was 38 cm (15 inches) off center. Another possibility is additional splashing causing losses from the MW at that high speed and at the larger Stokes numbers which correspond to larger MVDs.
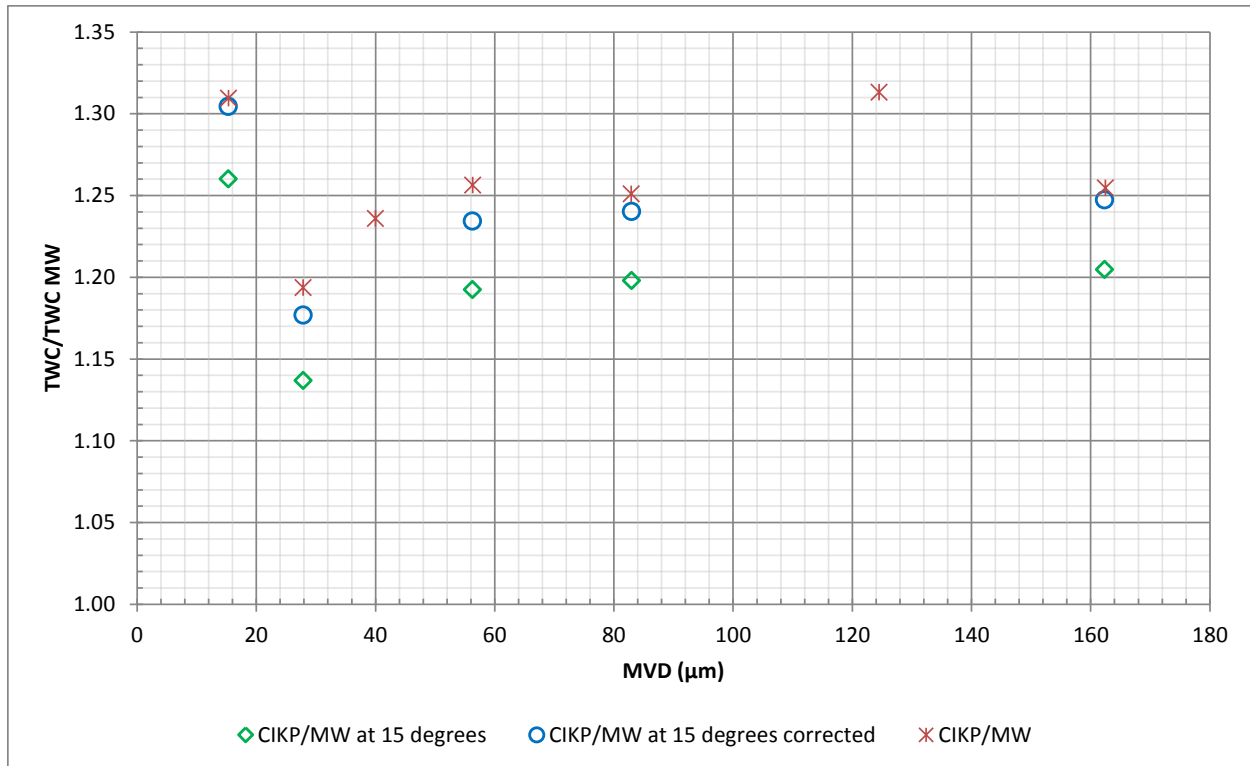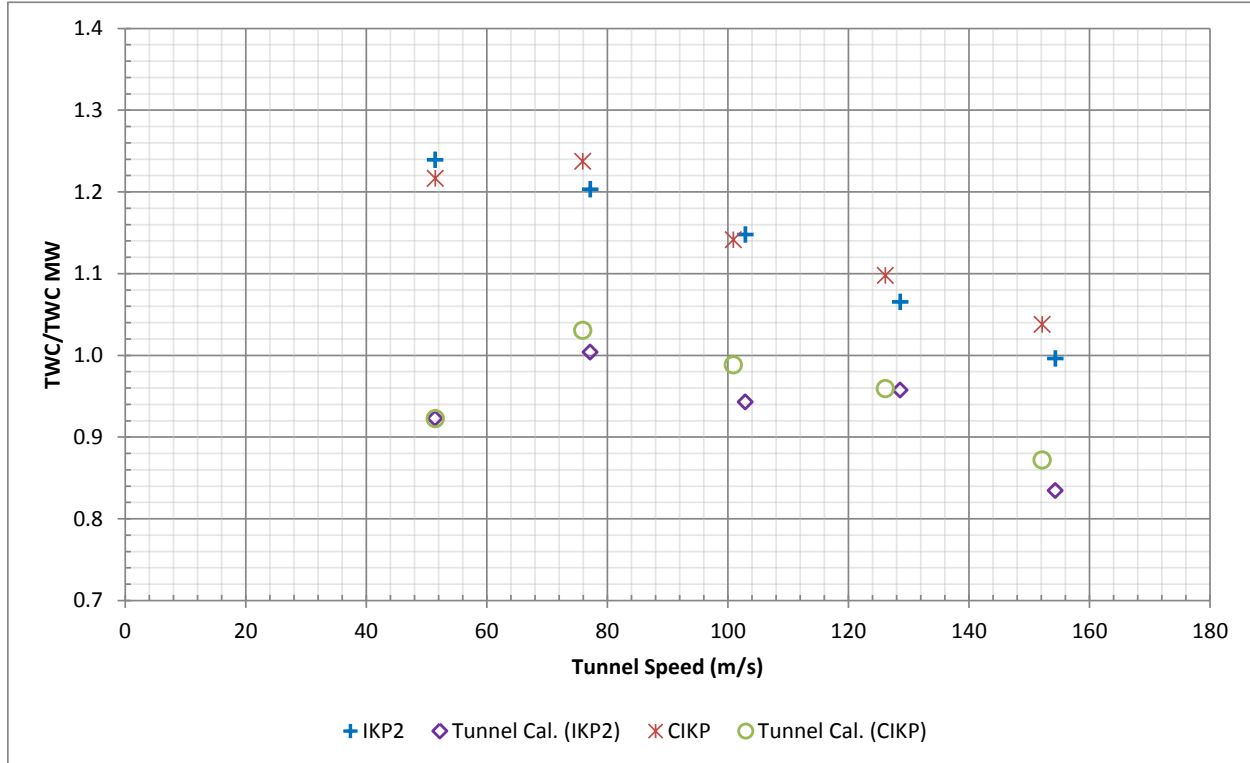
Figure 6. CIKP TWC divided by the corresponding MW TWC with varying MVD at T_o= -10°C, p_o=100 kPa, V=77 m/s and nominal LWC=0.54 g/m³
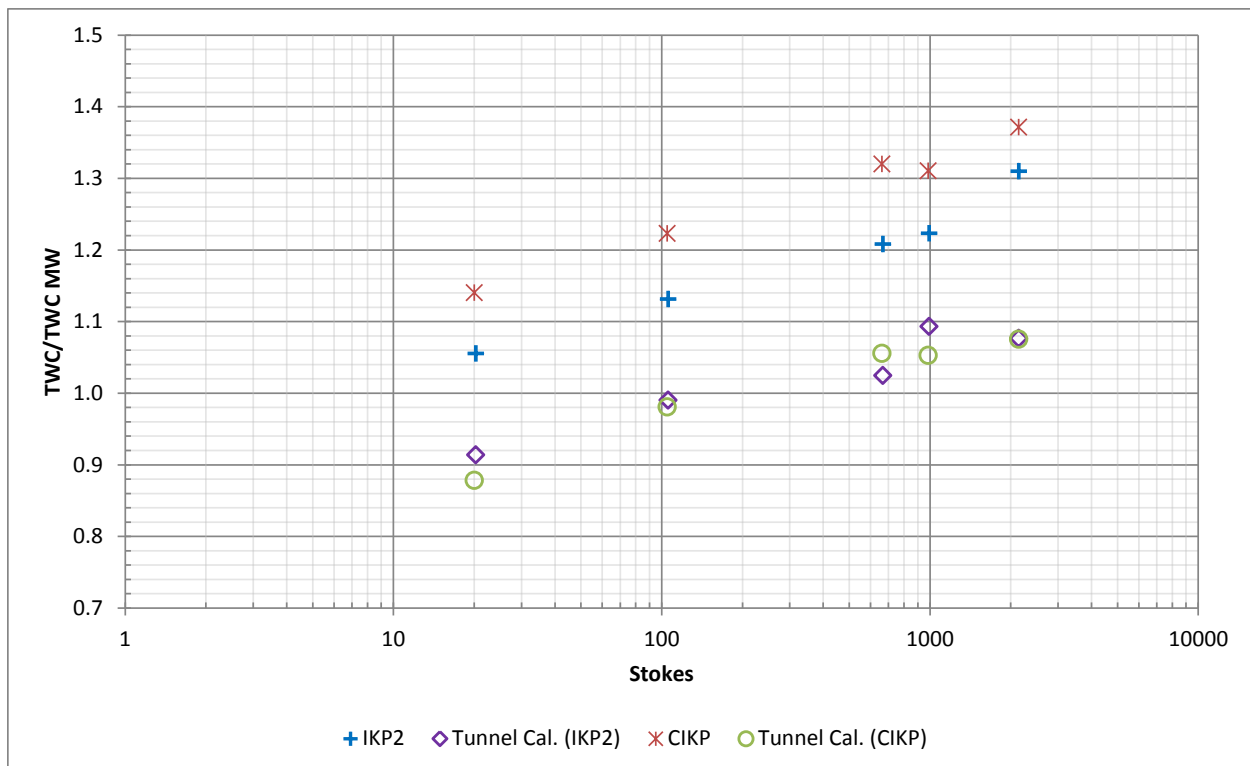
Figure 7. TWC divided by the corresponding MW TWC varying Stokes Number at T_o=-10°C, p_o=100 kPa, V=103 m/s, LWC=0.74 g/m³

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A sweep of tunnel velocities was also performed at an average MVD of 22 μm and 1.9 g/m³ LWC. The TWC results normalized by the MW TWC are presented in Figure 8. Excepting the lowest speed a decreasing trend is seen with increasing air speed for both the CIKP and the IKP2. A similar decreasing trend is seen for the tunnel calibration LWCs indicating that the trend may be a function of the tunnel LWC distribution at different air speeds, but, with exception of the 155 m/s case, the LWC variation is within ±10% tolerance indicated in IRT calibration reports[9]. When plotted versus Stokes number the trend is not apparent so it is dependent on air speed not on the capture efficiency of the probes. In this case the IKP2 and CIKP match very well.

Figure 8. TWC divided by the corresponding MW TWC with varying air speed at T_o=-10°C, p_o=100 kPa with average MVD=22 μm and LWC =1.9 g/m³

The effect of IKF on the CIKP results was evaluated at the IRT. The IKF is the ratio of air mass flow through the inlet to the air mass flow passing through an equivalent area in the freestream as given by eqn. (1). Two sweeps of IKF were performed at 77 m/s and 2 g/m³ LWC. The first at an MVD of 15 μm and the second at 45 μm corresponding to Stokes numbers of 5 and 46. The measured TWC was corrected by multiplying the measured or uncorrected TWC by the IKF shown by eqn. (2).

$$\text{IKF} = \frac{\dot{m}_{IKP}}{A_{inlet} V_\infty \rho_\infty} \tag{1}$$

$$TWC_\infty = \text{IKF} \cdot TWC_{uncorrected} \tag{2}$$

The correction to TWC assumes that all the droplets continue straight into the probe regardless of the IKF[10]. If some of the droplets follow the streamlines and do not enter the probe, the correction will over compensate. At high speeds and altitudes with large ice particles, Stokes near 2,500, it was shown that the compensation is accurate[7]. For this test, the IKF was varied from 0.7 to 1.3, well beyond the IKF that would be seen under normal operation. The control system maintains the IKF within 0.98 and 1.02 and is usually between 0.99 and 1.01. Under high speed conditions the probe is sometimes unable to maintain the required flow and the IKF can drop below 0.9. The results of the IKF sweep are presented in Figure 9. The TWC is normalized by the TWC at an IKF=1 to show the relative

changes. The uncorrected TWC varies significantly with the IKF but when the correction is applied the variation is reduced. The correction overcompensates since not all the particles that would enter the probe isokinetically actually enter the probe. Some follow the streamlines more closely and divert around the inlet at sub isokinetic flow or are drawn into the probe at super isokinetic flow. As would be expected the 15 µm sweep is more over corrected since the Stokes number is lower and the particles are more likely to follow the streamlines. However, with an IKF between 0.9 and 1.1 the error in the correction is within 2.5%, based on the slope of the least squares fit. Increasing the particle size to 45 µm reduces the error to 1.5%. Forcing the least squares fit through (1,1) does not change the slope within 2 significant digits.
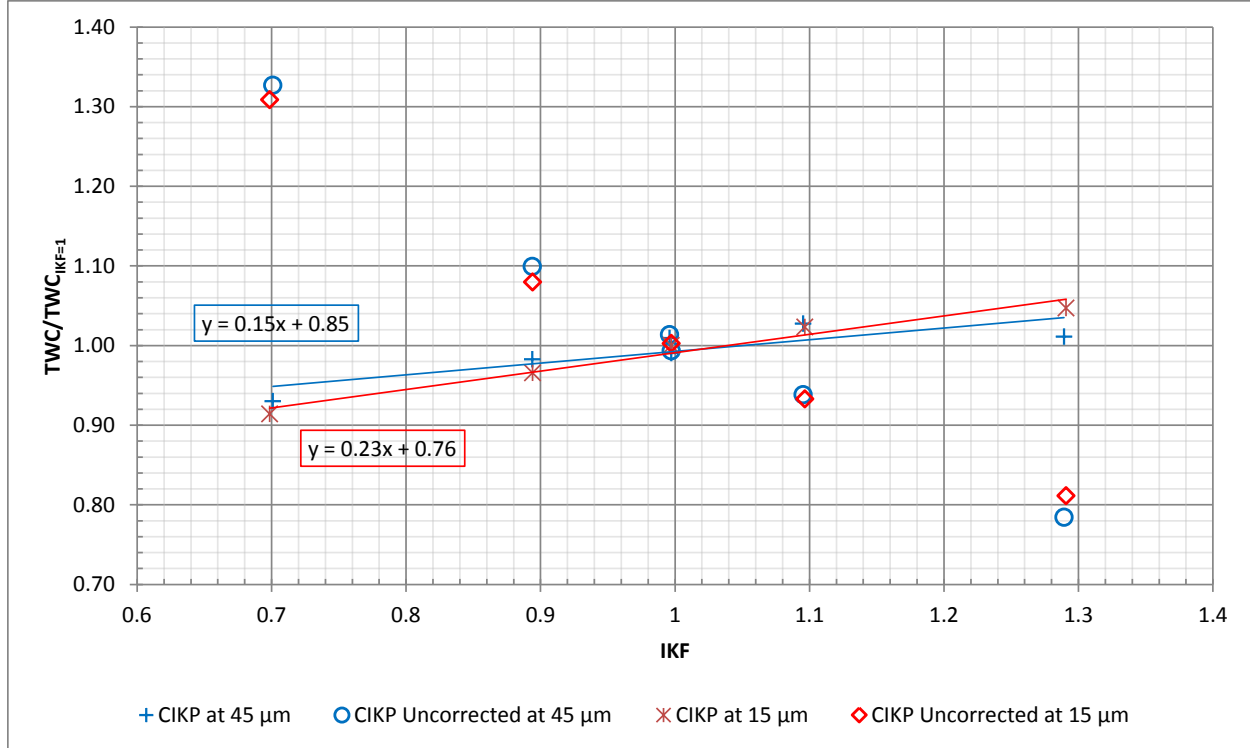
**Figure 9. TWC divided by TWC at an IKF=1 with varying IKF at T_o= -10°C, p_o=100 kPa with average V=77 m/s and LWC =2 g/m³ for sweeps with MVD=15 µm and 45 µm. Least squares fits to the corrected data are shown**

An extremely harsh condition was run to ensure the CIKP anti-icing system was adequate. The average speed was 152 m/s, total temperature was -10°C, MVD was 21 µm and the tunnel LWC was 2.7 g/m³. The transient results are presented in Figure 10. For the average results presented previously the sample was taken from 20 s after the spray was turned on to 2 s before it was turned off. Typically the sprays were on for 3 minutes. During the run no icing of the inlet was observed. Inlet icing events restrict the airflow into the IKP and the isokinetic factor drops off until the ice sheds and then it quickly recovers before dropping off again in a repeating cycle. Figure 10 shows this cycle was not present during the test, supporting the visual observations.

Due to the high speed and water content some water circulated around the tunnel as ice. As the test continues this appears as a rise in TWC, clearly seen in Figure 10, while the water delivered by the tunnel remains constant. The rise in TWC from the start of the spray to the finish is approximately 1.3 g/m³ which should be the quantity of ice circulating around the tunnel. Immediately after the spray is stopped the remaining TWC should be due to only the circulating ice and it was found to also be 1.3 g/m³. Once the spray is off, the ice falling out is no longer being replaced and the TWC continues to fall. Two spray bar systems were used to obtain the high LWC required for this test and at the end they were turned off several seconds apart. This drop in LWC is clearly evident in final portion of the spray. The background tunnel humidity is also shown in Figure 10. It starts at 1.25 g/kg which is above the static saturation level of 0.75 g/kg indicating that the air is supersaturated. However, it is below the total saturation level of 1.7 g/kg, as expected. Initially the background humidity rises, presumably due to evaporation in the slow moving section of the tunnel near the spray mast which is near the total conditions. After reaching a peak near 50 s

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the humidity begins to fall. A possible explanation is the additional ice particles providing a greater surface area for the supersaturated humidity to condense out on.
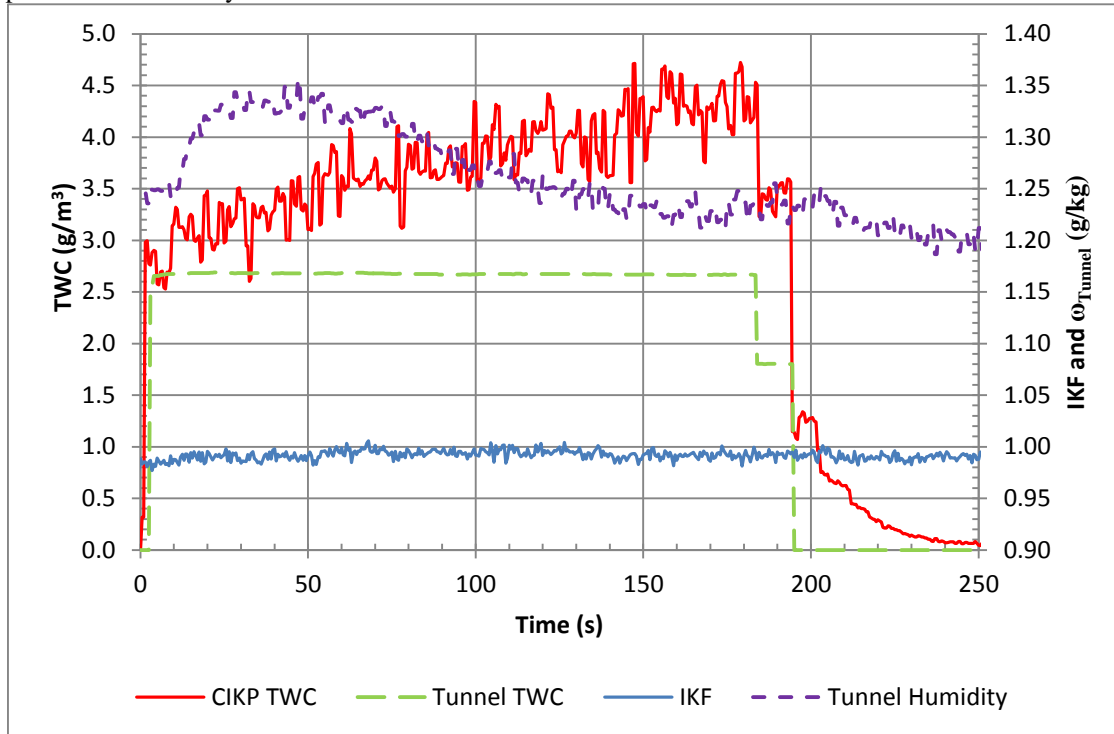
Figure 10. Transient results at V=152 m/s, T_o=-10°C, p_o=100 kPa, MVD=22 µm and LWC =2.7 g/m³

III.   Ice Crystal Testing

The compact IKP was tested and validated in the NRC sea level ice crystal tunnel, located in building M7 at the Ottawa facilities in February 2016. The IKP2 had been tested in the same facility in January 2016 and ice capture cylinders were used to measure the ice water content (IWC)[6]. The results from the IKP2 will be used to compare to the CIKP.

C. Experimental Set Up

The tests were performed over 2 days with nominal air speeds ranging from 76 m/s to 148 m/s and total temperatures from -19°C to -9°C. The measured IWC ranged from 0.6 to 12.7 g/m³. The tunnel is supplied with ice fed from four chutes shown in Figure 11. Figure 12 provides the overall layout of the tunnel. The ice crystal distribution is known to be non-uniform and the test section ice distribution has been mapped at a velocity of 150 m/s[11]. The ice was top quality clinebell ice supplied by Iceculture Inc. and is typically used for ice carving. It is free of air bubbles and other impurities, and has consistent density so the IWC is assumed to be proportional to the feed rate into the saw. Crystals were produced by grinding blocks of ice and the resulting median volume diameter ranged from 200 to 310 µm which increases with the ice saw feed rate[11].

The background humidity in the test section is required for the IKP to calculate the IWC. It was sampled using a rear facing tube with a flared inlet that is the NRC Gas Turbine Laboratory standard for measuring background humidity in icing tunnels. It is shown installed in the tunnel along with the CIKP in the center position in Figure 13. The probe could be manually traversed along the horizontal axis but was positioned at the tunnel center for the results presented here.
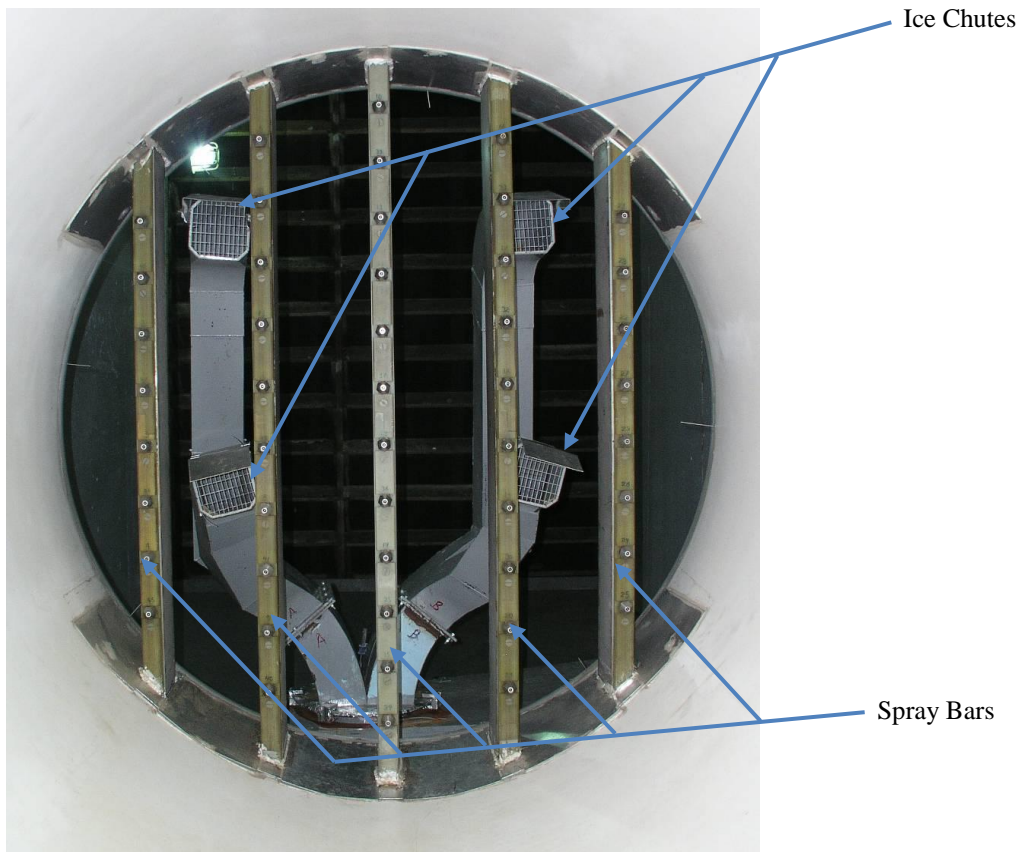
Figure 11. Inlet of NRC wind tunnel viewed from downstream position
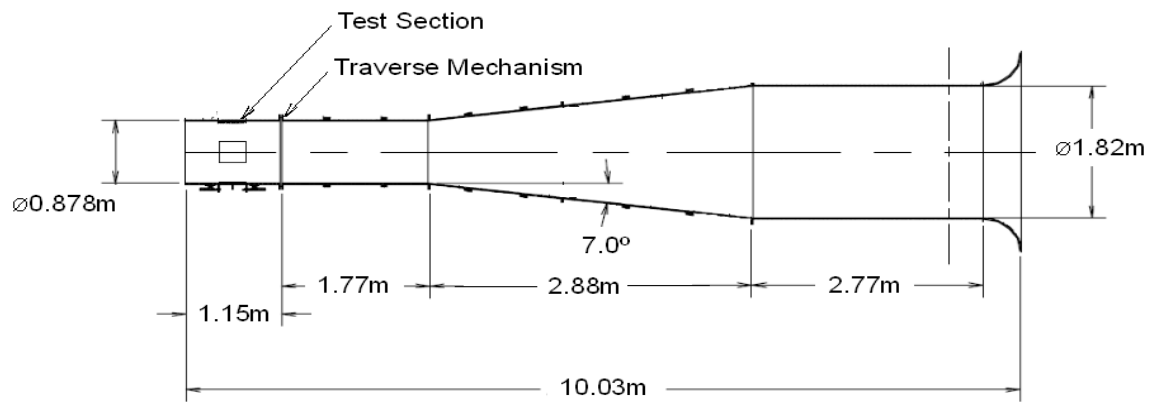
Figure 12. NRC wind tunnel layout
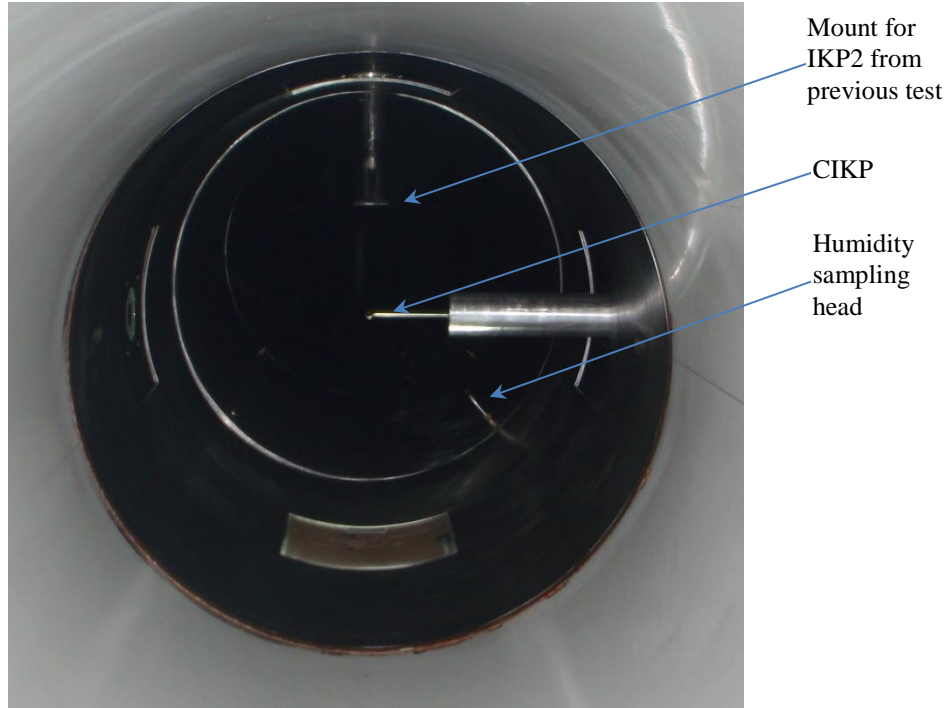
Figure 13. Test section configuration with flow in to the page

D. Results

To account for variations in air speed the TWC measured by the IKP was corrected to nominal air speeds with equation (3). As the air speed increases the corrected TWC also increases. This compensates for the fact that as the tunnel speed increases so does the volume flow of air and for a given feed rate of ice the TWC will decrease. This allows runs at different air speeds to be compared. Each sample was averaged over a different period time as the ice on time was limited by the feed rate and the length of the block of ice. The sample time was started once the ice flow had stabilized and ended approximately 2 seconds before the ice feed was ended. All the data within this time period was taken.

$$TWC_{corr} = TWC_{meas} \frac{V_{air}}{V_{air,nom}} \qquad (3)$$

Figure 14 shows the measured TWC from the CIKP across the range of feed rates near 145 m/s. The TWC is corrected to a nominal air speed of 150 m/s which was the standard speed for previous testing. Two samples were taken at each feed rate set point. The first set of samples was taken starting at the lowest feed rate and increasing to the highest. Once the first set was obtained sampling was repeated, again starting at the lowest feed rate and increasing to the highest.

The least squares line of best fit to the CIKP results almost passes through the origin as expected since at 0 feed rate the TWC should also be 0. The fit is very linear, also as expected since the feed rate is directly proportional to the ice entering the tunnel and the TWC. If the CIKP was saturating at higher IWC the curve would be expected to drop off at the high feed rates. For comparison the least squares fit to the data for the IKP2, obtained by Strapp et al.[6] is also presented. The fit presented here does not match that presented by Strapp et al. as the TWC correction is slightly different. The CIKP measures approximately 1% lower the IKP2 based on the linear best fits. The measurement uncertainty on the CIKP results shown in Figure 14 range from 3.6% at the lowest TWC to 2.3% at the highest based on the method presented by Davison et al.[10] The confidence interval for the best fit line for the CIKP is presented in Table 2. The 95% confidence interval on the CIKP result includes the IKP2 result. Given the instrument uncertainty and the uncertainty due the variation in the results the CIKP and IKP2 results and the variation in the tunnel operation, the IKP2 and CIKP were considered to match.

Table 2. Least squares linear best fit to CIKP and IKP2 results at 150 m/s with the upper and lower 95% confidence intervals for the CIKP

| Instrument	Corrected Air Speed (m/s)	Slope (TWC/F)		TWC-intercept	
CIKP	150 m/s	0.064	0.068	0.02	0.23
			0.059		-0.19
IKP2	150 m/s	0.065		-0.01	
CIKP	80 m/s	0.148	0.166	-0.59	-0.19
			0.131		-0.98
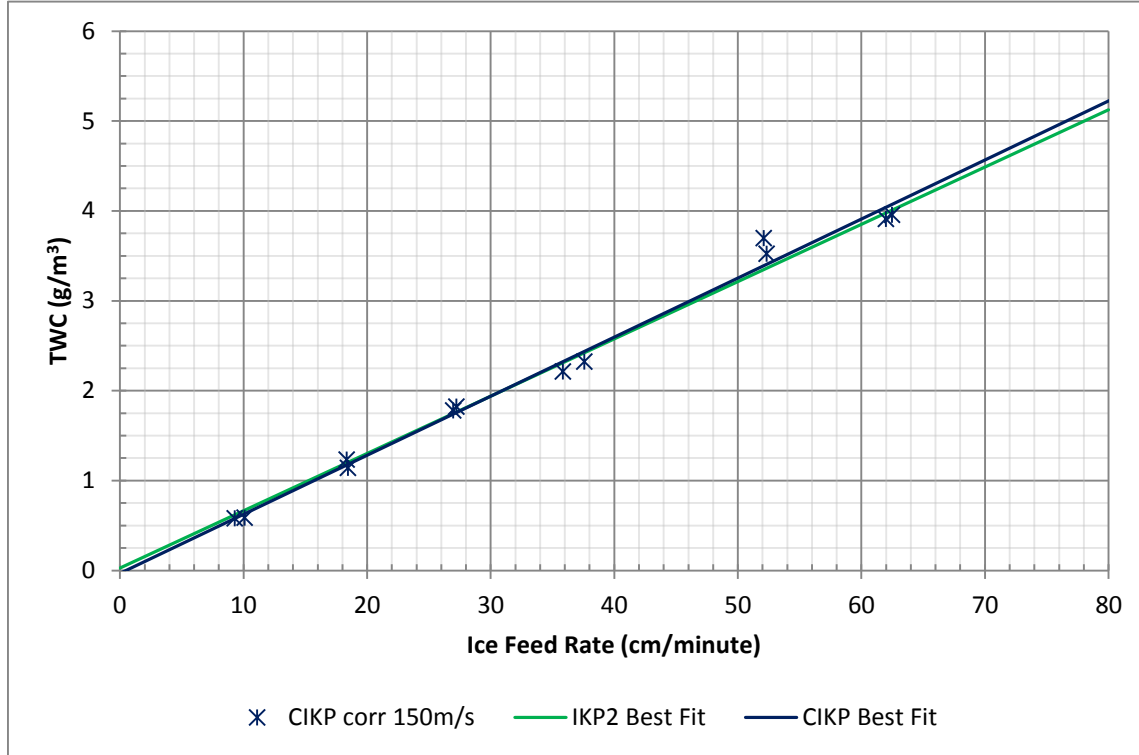
Figure 14. Corrected TWC versus ice feed rate measured by CIKP near 145 m/s

TWC was also measured with the CIKP near 80 m/s air speed. In this case the TWC was corrected to a nominal air speed of 80 m/s and the results are presented in Figure 15. The line of best fit does not come as close to the origin as at 150 m/s but with a single set of data, and no comparison instrument at this speed, it is difficult to make any conclusions, but if combined with the data set at 150 m/s more can be determined.
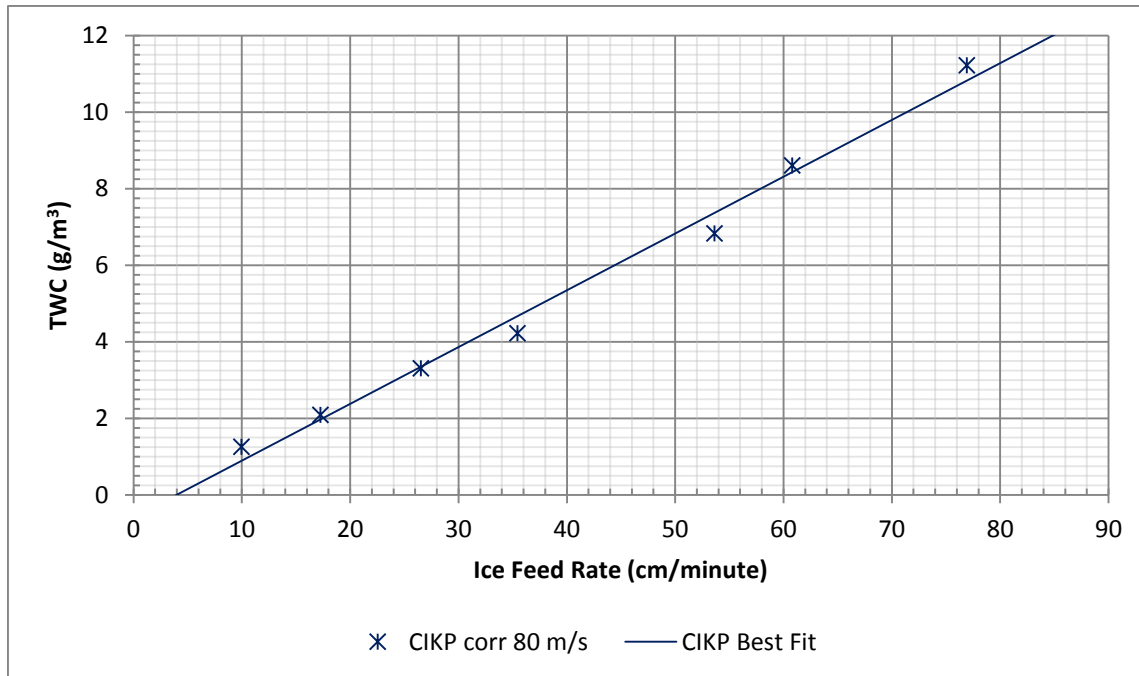
Figure 15. Corrected TWC versus corrected ice feed rate measured by CIKP near 80 m/s

To compare the results at 80 m/s to those at 150 m/s the ice ingestion rate needs to be considered. The ice ingestion rate is the mass flow rate of ice into the CIKP. Assuming that the relative distribution of ice across the tunnel area does not change with tunnel speed the ice ingestion rate should only depend on the ice feed rate. For this comparison the results do not need to be corrected to a nominal speed as they are independent of the air speed. This is presented in Figure 16. The results below 60 cm/s feed rate match very well for both speeds. Above 60 cm/s they show much greater variation. This variation seems to be a tunnel behaviour as the results of Strapp et at.[6] showed a large variation with both the IKP2 and ice capture cylinders above 60 cm/s. At 50 cm/s the IKP2 found a 17% variation over four sample points and the ICC 18%. Near the 60 cm/s feed rate the IKP2 found a 22% variation over four points and the ICC 29%. With three samples the CIKP found a 5% variation near 50 cm/s and a 15% variation near 60 cm/s. With large variations and small data sets, a single point can have a large effect on the line of best fit. In the region below 50 cm/s which showed greater stability in tunnel operation the results for 80 m/s and 150 m/s are very consistent indicating that the tunnel speed is not having an effect on the results. In early versions of the IKP, saturation of the vaporiser was observed at 80 m/s and these results indicate that issue has been eliminated in this version of the IKP. The limited data set at the higher feed rates does not indicate a saturation problem as the higher ingestion rates correspond to the lower speed while saturation would cause a lower ingestion rate.
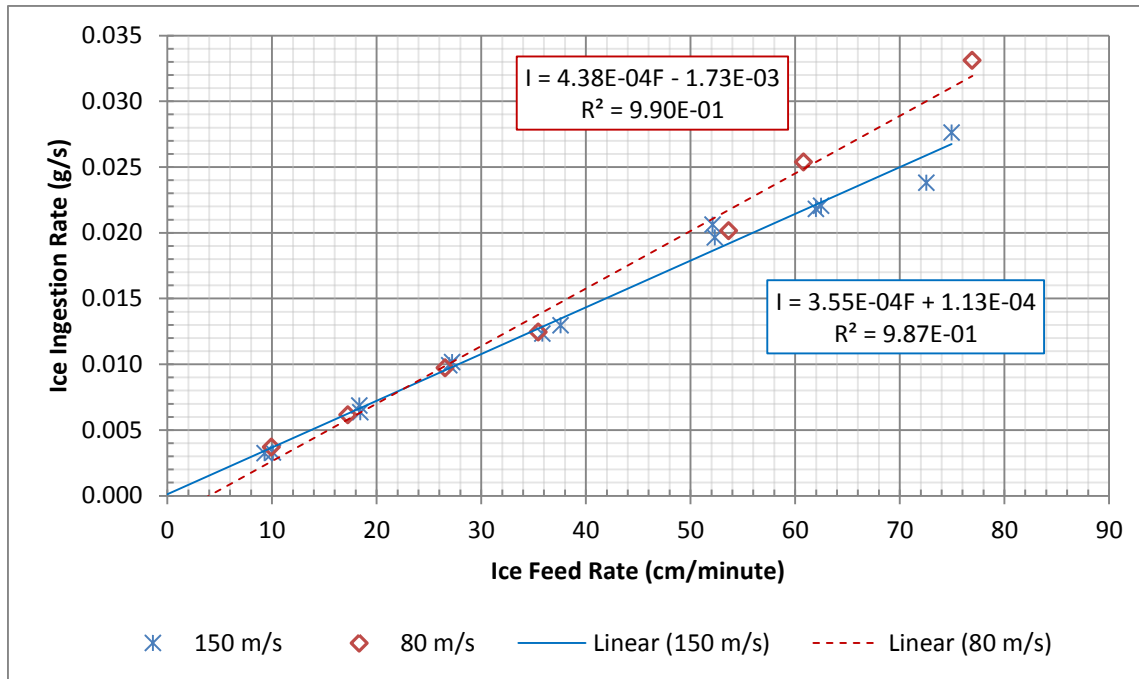
Figure 16. Ice ingestion rate versus feed rate for 80 and 150 m/s

Figure 17 shows the transient response of the IKP during a run. The IKP TWC measurement increases once the ice grinder engages the ice block and the TWC measurement rapidly drops off once the ice grinder has been disengaged. This indicates that no ice is left in the IKP which would result in a lower reading, due to the deposited ice, during the time the ice is flowing. Some TWC is seen after the grinder has disengaged due to ice dislodging from the ice delivery system. The large variations in ice flow are typical of the tunnel, especially at high feed rates such as this one, which is at the maximum of the system.
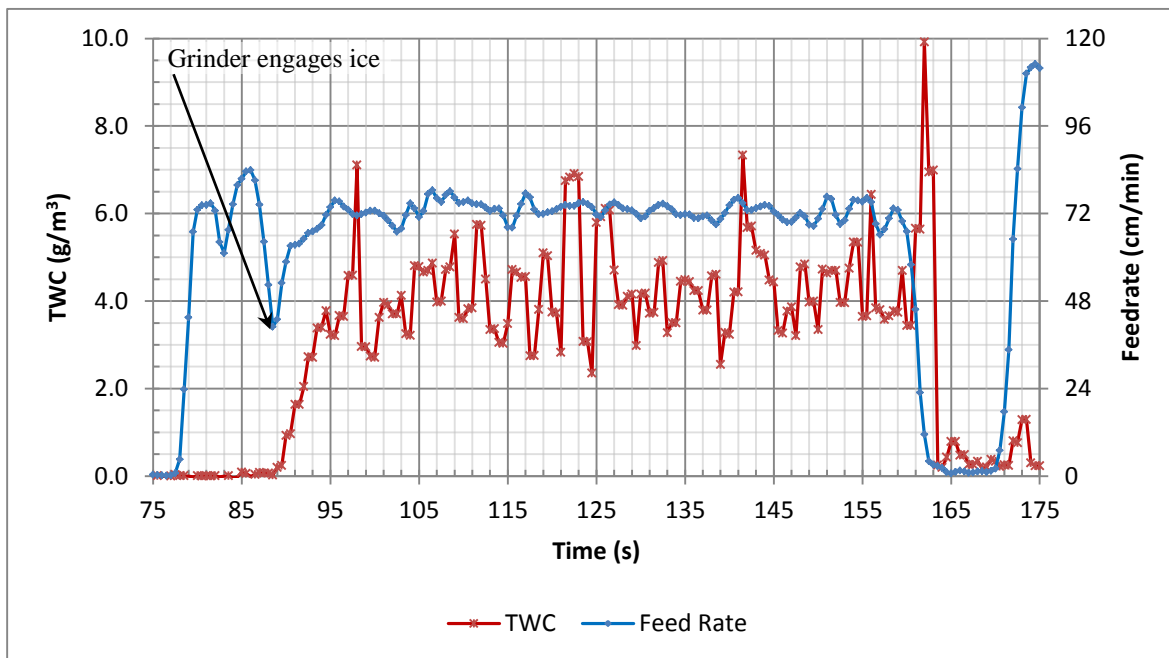
Figure 17. TWC from IKP and ice feed rate with time at a tunnel speed of 147 m/s, T_o=-14°C

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IV. Aerodynamic Testing

The compact IKP flow path can be sealed enabling it to function as a pitot probe. This allows the aerodynamic condition to be partially characterized when no dedicated pitot probe is available. This is useful as the IKP can be deiced under very severe conditions. During the testing at the IRT, the IKP was rotated through 15 degrees and the variation in total pressure characterized. Figure 18 shows the deviation from tunnel pressure, given by equation (4), versus the angle of attack (AOA) of the IKP. Although there is a constant offset ranging up to about 0.15% it does not appear to depend on angle of attack up to 15°.

$$\text{Deviation} = \frac{p_{oIKF} - p_{oTunnel}}{p_{oTunnel}} 100\% \tag{4}$$
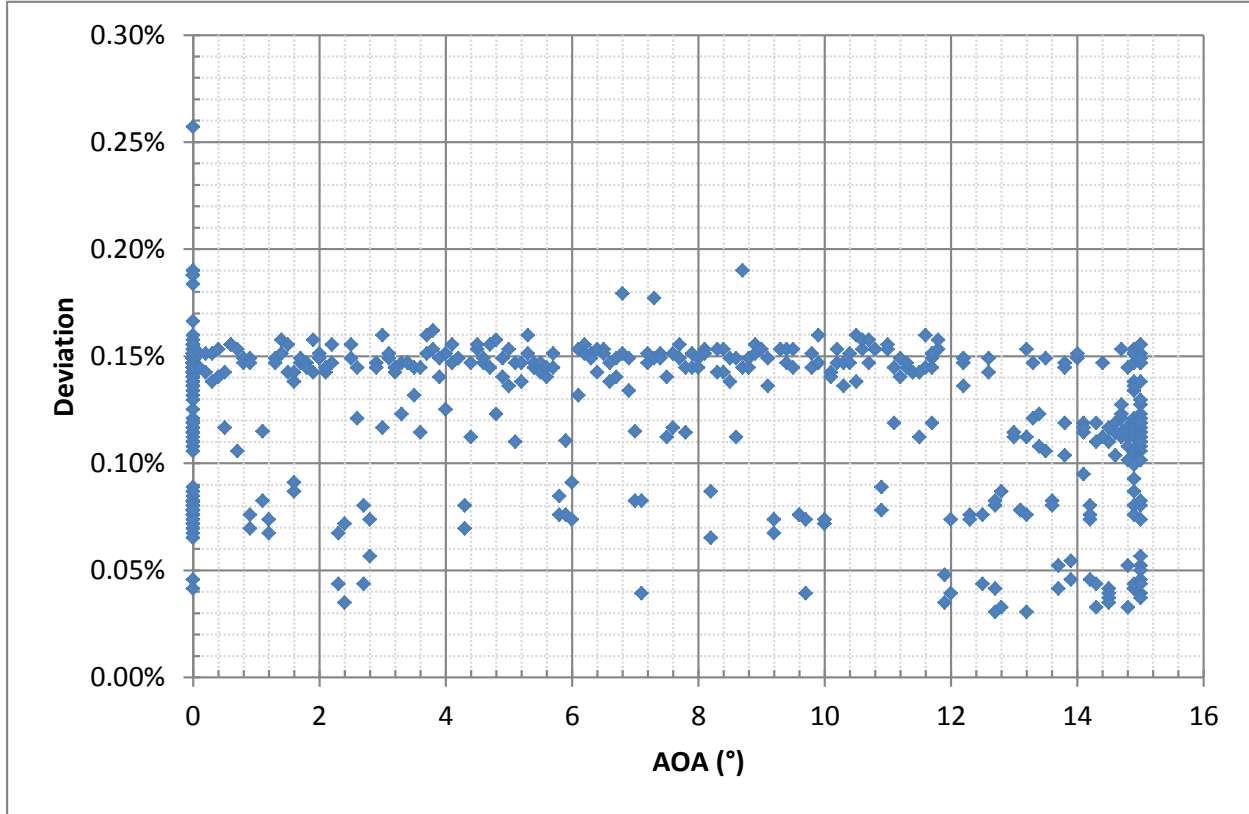

Figure 18. Deviation in total pressure measured by IKP compared to total pressure reported by the tunnel

V. Conclusions and Future Work

The CIKP was tested at the IRT under super cooled liquid conditions and in the NRC sea level ice crystal tunnel. During the TWC sweeps performed in each tunnel the CIKP matched the IKP2 within 3% for the best data sets (77 m/s at the IRT and the 145 m/s at NRC). The remaining two LWC sweeps at the IRT matched within 4.5%. The CIKP showed no signs of saturation or of icing. At lower Stokes numbers the TWC cannot be fully corrected for operation at IKFs not equal to 1 but at a Stokes number of 5 could be corrected to 2.3% of the TWC at IKF of 1 for every 0.1 change in IKF and to 1.5% for a Stokes number of 45. The total pressure measured was offset by 0.15% from the total pressure reported by the IRT but independent of AOA up to 15°.

Future work for the tunnel IKP includes modifying the leading edge heat to estimate LWC in mixed phase environments. The objective is to be able to separate the TWC measured by the IKP into LWC and IWC components.

Acknowledgments

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