Development of Snow Test Capabilities at National Research Council of Canada (NRC)

National Research Council of Canada

Ice Genesis: November 3, 2022

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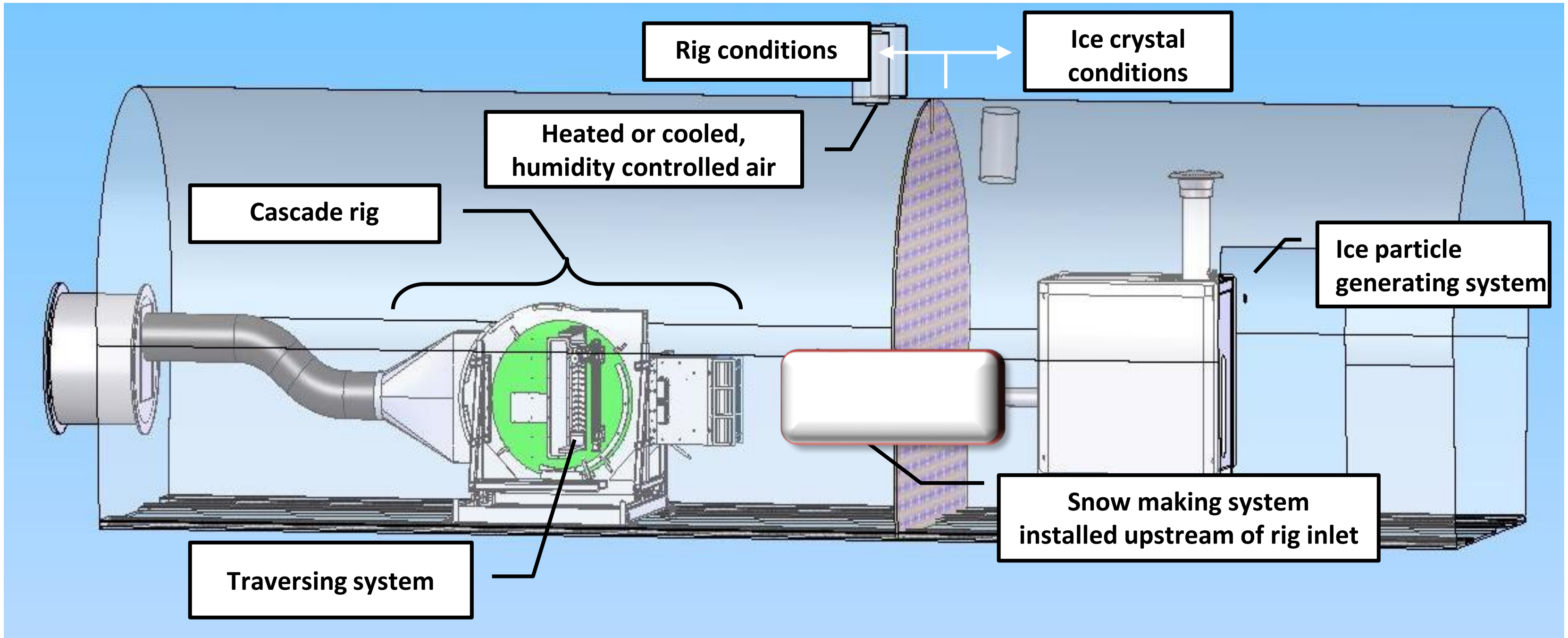
NRC snow maker installed in the NRC Research Altitude Test Facility (RATFac)

- Flow through facility, i.e. no recirculation
- Cascade rig has ice crystal icing instrumentation ideally suited for snow: temperature, pressure, speed, TWC, all in dry or wet conditions
- Operating range based on 13 x 25 cm x-section →

Param.	Min.	Max.	Unit
T_0	-40	+40	[°C]
Alt	100	15,000	m
Vel	20	250	m/s
RH	1	100	[%]



NRC·CNRC

NRC snow maker installed in the Research Altitude Test Facility (RATFac)

- A full-scale prototype NRC snow maker was tested in the summer of 2021 and an upgraded version in summer 2022
- Snow particles are created by agglomerating small ice particles, not freezing out so there is no supercooled liquid water as seen in other techniques like snow guns
- Modifications to the NRC Iso-kinetic probe were done to improve the measurement accuracy in the low TWC range, i.e. <1 g/m^3
- Particle sizing done with backlit, high resolution imaging
- Summary of falling snow envelope achieved:
  - TWC: 0.2 to 2.5 g/m^3 (V_tunnel=40 m/s)
  - Dv50*: 1 to 4 mm
    - For dry snow or longer test durations (t >15 minutes), 1 < Dv50 < 2.5 mm
  - Snow bulk density** (dry): 155 to 205 kg/m^3
  - Velocity: 20 to 105 m/s
  - Temperature: -15 to +2 oC
  - Wet and dry snow
  - Test durations: 2 to 60 minutes

Snow being collected for bulk density measurement
T= -5°C, Dv50 = 1.5 mm (TP897-21)

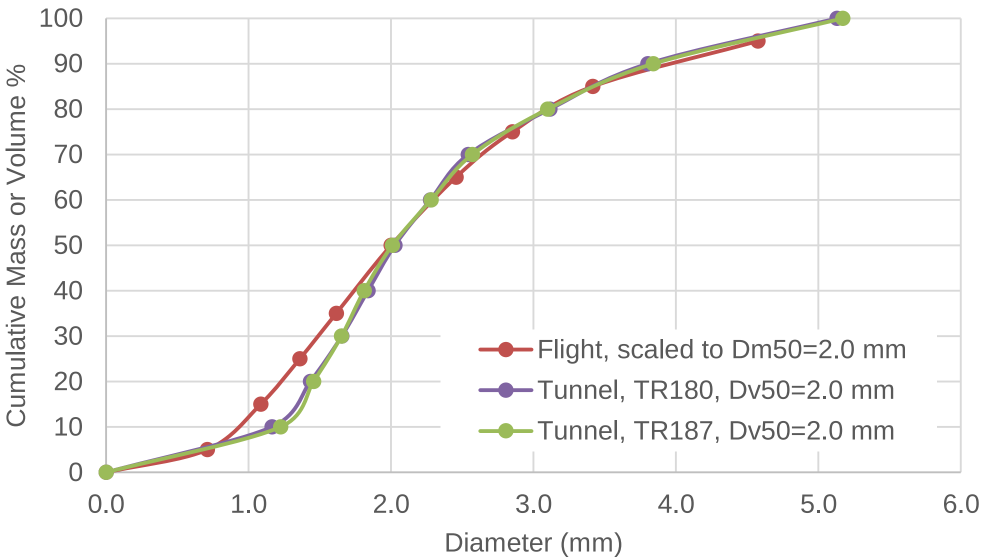
* Particle density vs. diameter is not yet known so size being reported based on equivalent spherical volume and not mass

** Natural snow is 34 to 720 kg/m^3 with dry snow typically below 200 kg/m^3

Falling snow particle characteristics

- Although Dv50 is used as a defining parameter for particle size, the distribution is also of interest
- Scaling the flight data to a Dm50=2.0 mm, it can be compared to snow maker test points at that Dv50
- Since the snow maker particle density is unknown, volumetric measurements are the only comparable option
- Results show excellent agreement where there is only a small difference in the 1 to 2 mm size range
- The two tunnel repeat points are in excellent agreement showing good repeatability

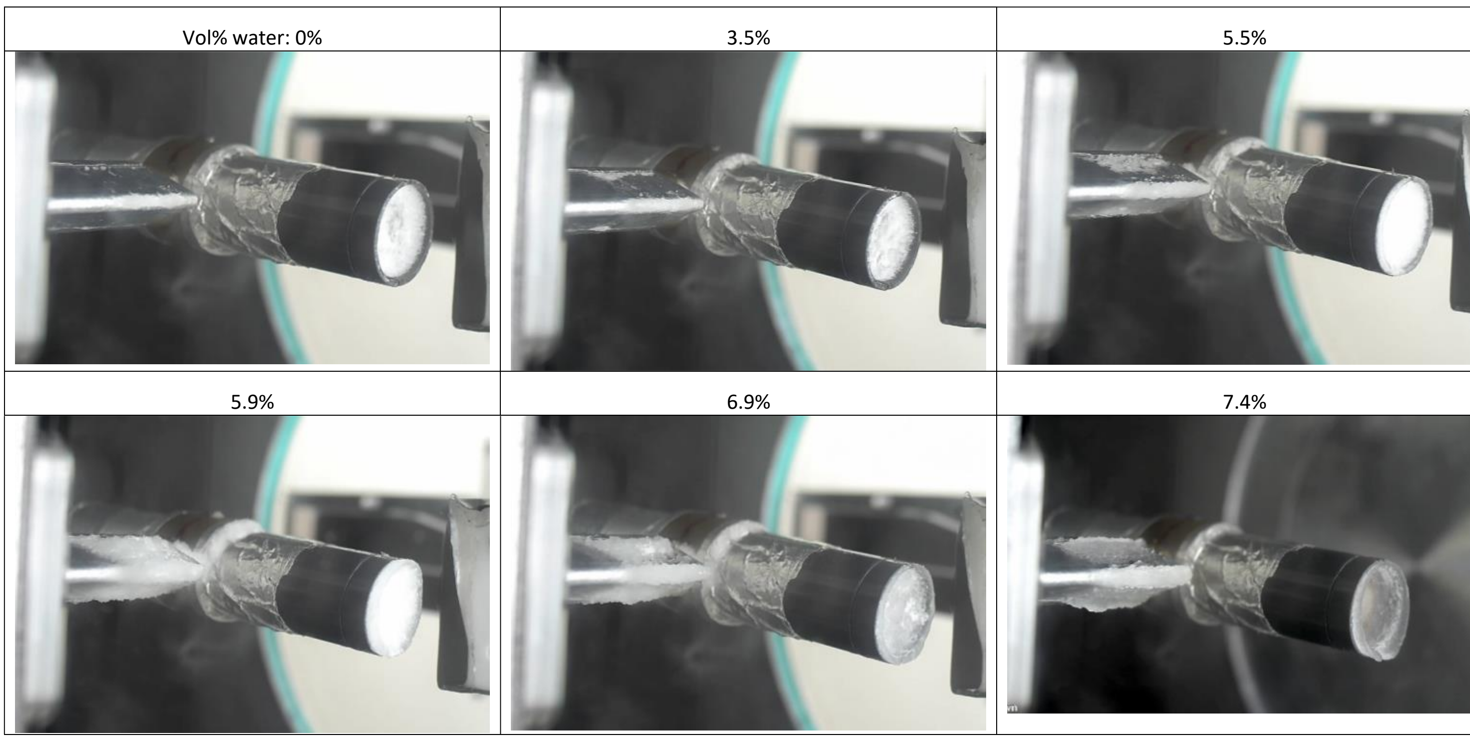
Sample high resolution shadowgraphy image used for particle size distribution measurement (TR103-22)



Cumulative particle size distribution: tunnel versus flight

Control and measurement of melt

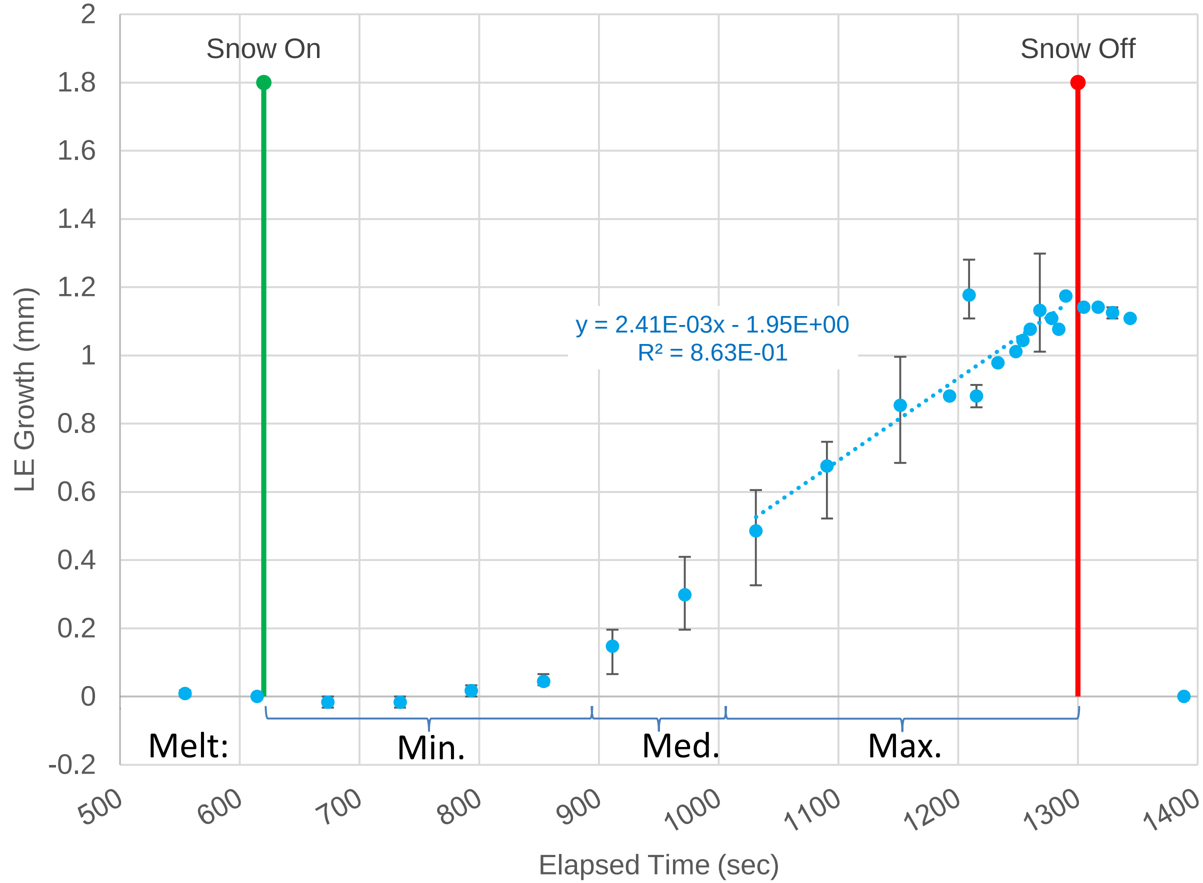
- The NRC snow maker system has the ability to independently change particle melt
- The NRC ice property probe (IPP) can measure the %melt, i.e. volume percent of water
- A range of snow conditions show the change in %melt and the difference in visual appearance
- Drier snow is white and granular/rough
- Lower melt has less accretion on IPP inlet and strut
- Wetter becomes more transparent and smoother, i.e. slush like
- In good agreement with “water percolation” observations by Ebner et al



Images of increasing vol% melt measured by the Ice Property Probe (IPP)

Growth rate versus melt

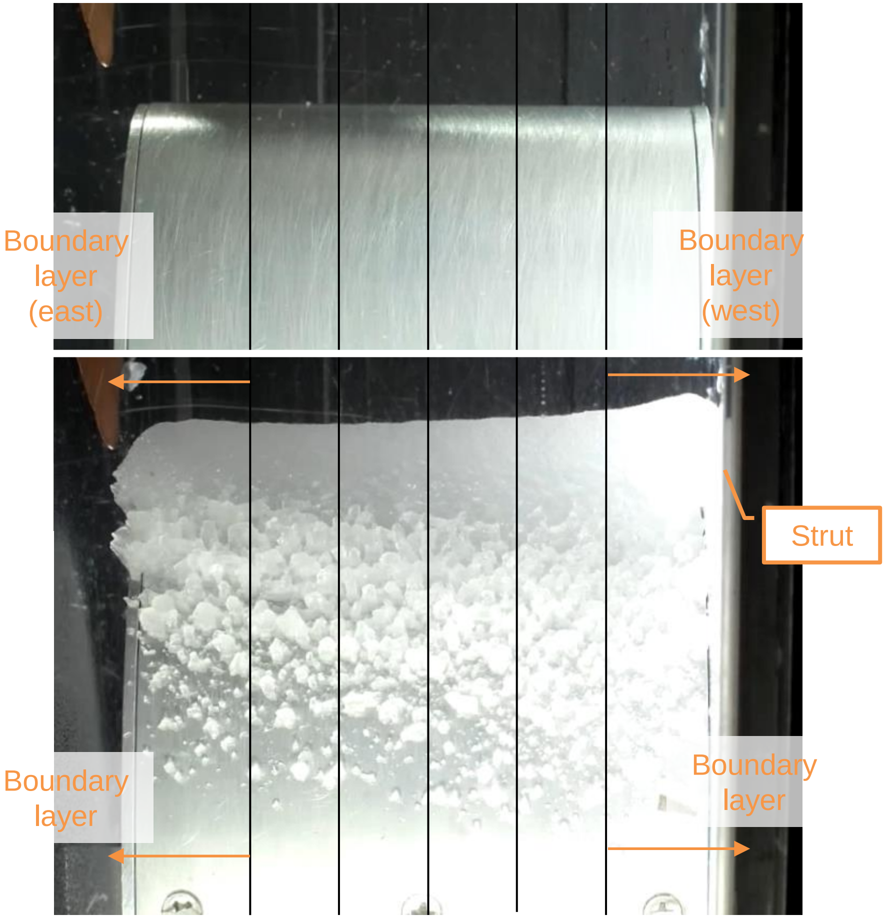
- Imaging of the NACA0012 airfoil allows measurement of the leading edge (LE) growth rate
- Results show that the first level of melt did not produce any notable accretion
- At the higher melt, ice accretion starts and its growth rate is linear
- This indicates the importance of having the right amount of melt for accretion to even occur



LE ice growth rate for TP876-21
Error bars based on resampling 3 times

Snow maker TWC spatial uniformity

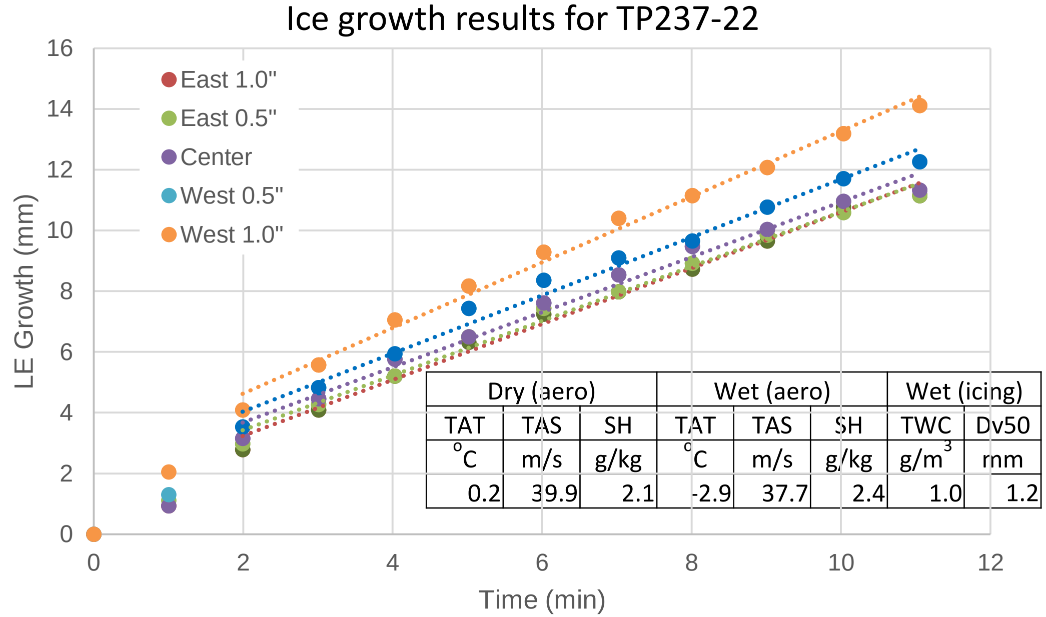
- The snow maker system has the ability to fine tune particle trajectories that affect uniformity
- The IKP is typically used for tunnel TWC uniformity measurements
- However, it was modified for another project resulting in an inability to conduct long duration measurements required for this measurement
- Fortunately, uniformity can also be examined by looking at the LE ice growth on the airfoil
- The edges of the airfoil are inside the tunnel boundary layer (BL) and right side also affected by strut, these regions are therefore ignored



Top view of NACA0012 airfoil, top image=clear, bottom image=ice growth after 11 minutes, black lines are locations of growth rate measurements, TP237-22

Snow maker TWC spatial uniformity

- The snow maker system has the ability to fine tune particle trajectories that affect uniformity
- The growth reaches a linear rate after about 2 minutes where they have a high regression coefficient of 0.99
- The five growth rates across the span are well within the desired ±20% of the average showing good uniformity
- Using growth rate also considers tunnel aero and snow conditions so is a worst case condition



Dry (aero)			Wet (aero)			Wet (icing)	
TAT	TAS	SH	TAT	TAS	SH	TWC	Dv50
°C	m/s	g/kg	°C	m/s	g/kg	g/m^3	mm
0.2	39.9	2.1	-2.9	37.7	2.4	1.0	1.2

Location	distance from centerline	LE growth rate	
	in	mm/min	Relative to Avg.
West	-1.0	1.08	13%
	0.5	0.96	1%
Center	0.0	0.90	-6%
East	+0.5	0.91	-5%
	+1.0	0.92	-4%
	Average:	0.95	
	1SD:	0.074	
	1SD%:	7.8%	
	Limit:	20%	

Snow maker Dv50 spatial uniformity

- The particle imaging was setup so PSD measurements are made at the top, middle and bottom thirds of the tunnel at its inlet
- The depth of field (DOF) is the width of the tunnel so spatial data can only be taken vertically
- Three test points are examined over a range of particle sizes where all the data was within ±4%
- There is no Dv50 spatial requirement but using the repeatability number as a desired limit, the uniformity is within the desired ±10%

Tunnel section	TP237	%above avg.	TP253	%above avg.	TP202	%above avg.
Top $1/3^{rd}$	1.11	1.2%	1.69	-4.5%	2.51	1.6%
Middle $1/3^{rd}$	1.09	-0.6%	1.80	1.7%	2.46	-0.4%
Bottom $1/3^{rd}$	1.09	-0.6%	1.82	2.8%	2.44	-1.2%
Average:	1.10		1.77		2.47	
1SD:	0.01		0.07		0.04	
1SD%:	1.1%		4.0%		1.5%	
Desired:	10%		10%		10%	

Dv50 spatial uniformity

Snow maker TWC and Dv50 temporal uniformity

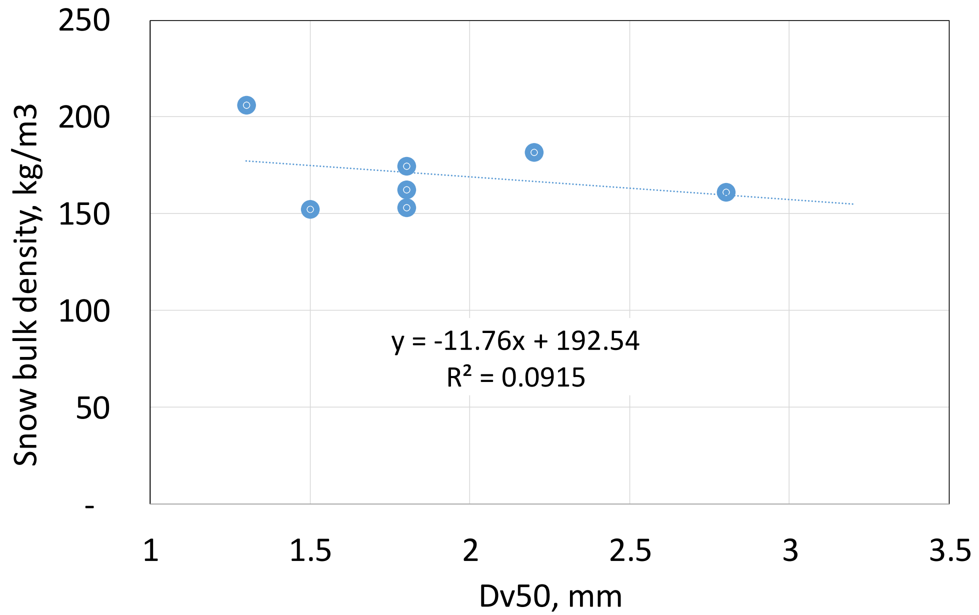
- The IKP configuration was not able to measure TWC continuously during a test point
- This meant TWC measurement could only be made periodically
- Each TWC measurement was 40 to 50 seconds in duration
- The TWC vs time shows a variation of ±6% for 1SD, well within the desired ±20%
- Measuring the Dv50 along the same timeline shows a variation of ±2% for 1SD, well within the desired ±10%

Time from snow on	TWC	Relative to Avg.	Dv50	Relative to Avg.
min	g/m3	%	mm	%
0.5	2.15	-2.5%	1.30	-2.3%
3.5	2.40	9.1%	1.37	3.0%
7.3	2.10	-4.4%	1.32	-0.7%
11.0	2.15	-2.2%	1.33	0.0%
Average:	2.20		1.33	
1SD:	0.13		0.023	
1SD%:	6.1%		1.7%	
Desired:	20%		10%	

Sample of TWC and Dv50 versus time (TP253)

Snow maker bulk density

- Used a standard falling snow bulk density measurement method where snow particles were captured in pans
- Snow was leveled off by cutting off snow above the top with careful attention not to compact the particles
- A range of dry snow particle sizes were measured, having an average bulk density of 170 kg/m³
- This is in good agreement with natural dry snow at 170 kg/m³ for 1 mm diameters*
- The bulk density slowly decreases with increasing particle size which is in agreement with literature*
- Three repeat runs show the repeatability to be ±15% for one standard deviation, close to the desired maximum ±20%



DAS scan#	kg/m3	%above avg.
894	163	-5.2%
899	195	13.4%
899	154	-10.5%
Avg.	172	
1SD	26	
1SD%	14.9%	
Desired:	20%	

Repeat bulk density measurements

* Szilder, Krzysztof. "Snow accretion prediction on an inclined cable." Cold Regions Science and Technology 157 (2019)

Ice genesis snow testing criteria

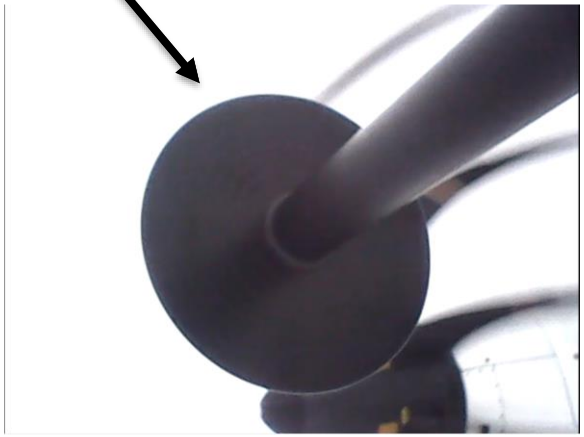
- Although repeatability is not specified, it is a good parameter to quantify to provide confidence in the test system
- The test parameters should meet the tunnel spatial variability criteria
- Three repeat test points were run where between points, the tunnel was brought off point where all parameters were changed to clear the accretion and then the next point was set up
- The results show both aero and snow parameters to be very repeatable and within the desired spatial tolerances (shown in green)
- Although there is no requirement on growth rate, ±5.3% shows good tunnel repeatability as this is affected by all tunnel parameters
- Also of interest is the drop in temperature from dry to wet
- This is as expected given the cooling due to colder particles and evapouration and should be considered in setting up a test point

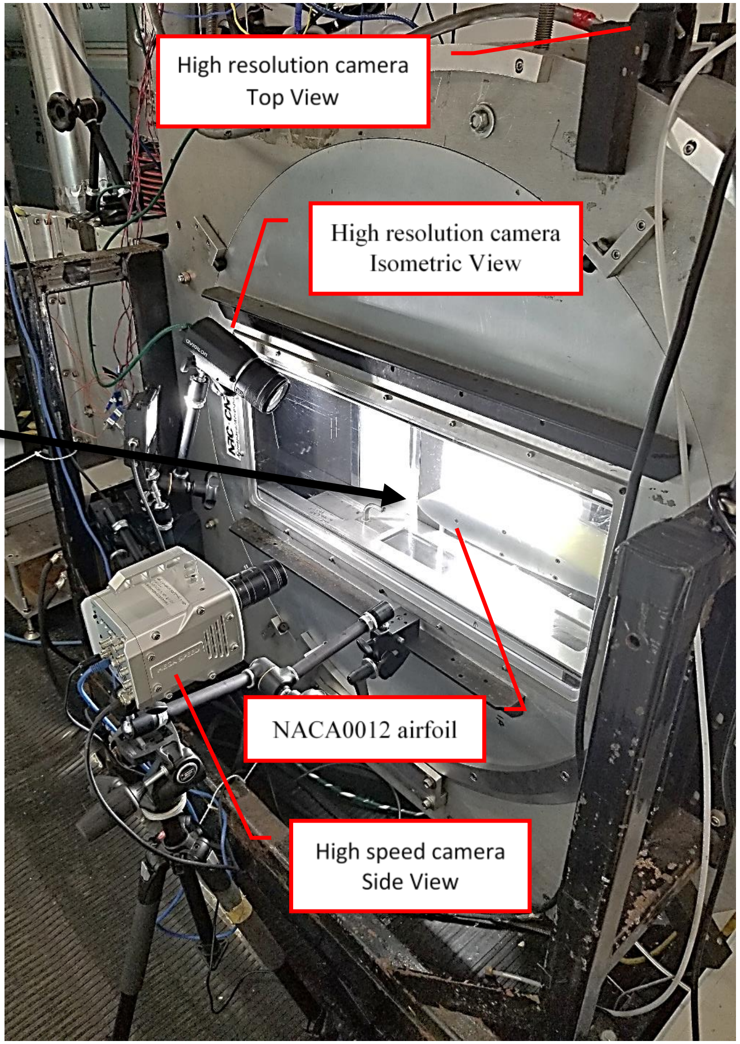
Test ID	Dry (aero)				Wet (aero)				Wet (icing)			
	TAT	TAS	Alt	Humid.	TAT	TAS	Alt	Humid.	TWC	Dv50	Melt	Max. LE growth rate
	°C	m/s	m	g/kg	°C	m/s	m	g/kg	g/m^3	mm	%water	mm/min
174_22	-0.7	40.9	91.4	1.59	-1.3	40.0	91.4	1.64	0.64	1.9	6.8	0.70
178_22	-0.5	40.5	91.4	1.49	-1.5	40.1	91.4	1.62	0.97	1.9	7.0	0.80
180_22	-0.3	39.8	91.4	1.48	-1.6	36.6	91.4	1.69	0.79	2.0	7.4	0.76
Average	-0.5	40.4	91.4	1.52	-1.5	38.9	91.4	1.65	0.80	1.9	7.1	0.75
1SD	0.2	0.5	0.0	0.0	0.1	1.6	0.0	0.0	0.13	0.0	0.2	0.04
1SD%	NA	1.1%	0.0%	3.3%	NA	4.2%	0.0%	1.8%	16.9%	2.4%	3.5%	5.3%
Desired[1] ±	1.0	2%	50	NA	NA	NA	NA	NA	20%	30%	25%	NA

1-Based on spatial limits defined in the Ice Genesis snow calibration methodology, Del7.1

Artificial snow accretion vs. flight

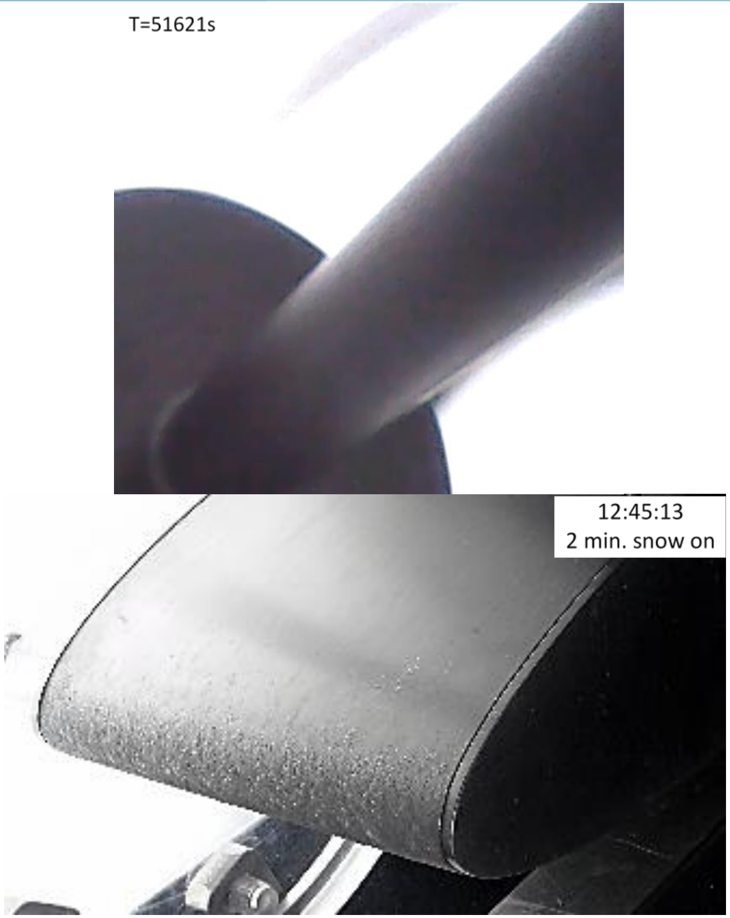
- To examine the representativeness of the artificial snow environment, accretion observed on a NACA0012 airfoil in the tunnel is compared to accretion seen in flight
- For accretion observations:
  - Tunnel: NACA0012 airfoil, unheated, AOA=0º
  - Flight: Cylinder perpendicular to the flow





Artificial snow accretion vs. flight

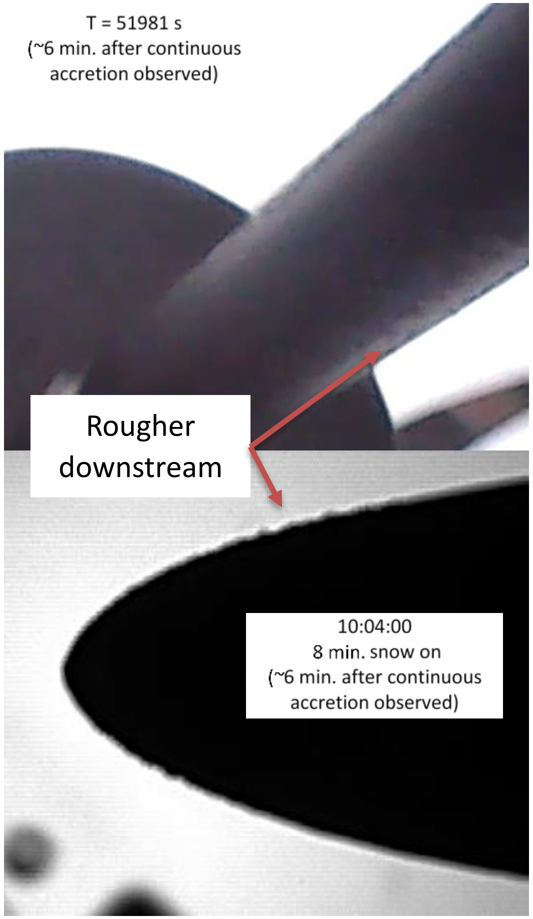
- The tunnel aero and snow conditions were set to match those measured in flight
- In flight, the accretion started with an even coverage with a rough or dimpled surface
- A similar characteristic is seen for the tunnel airfoil after approximately 2 minutes of snow exposure



Comparison of flight (top) to airfoil accretion (bottom) both showing even, dimpled, continuous coverage at early stage of accretion

Artificial snow accretion vs. flight

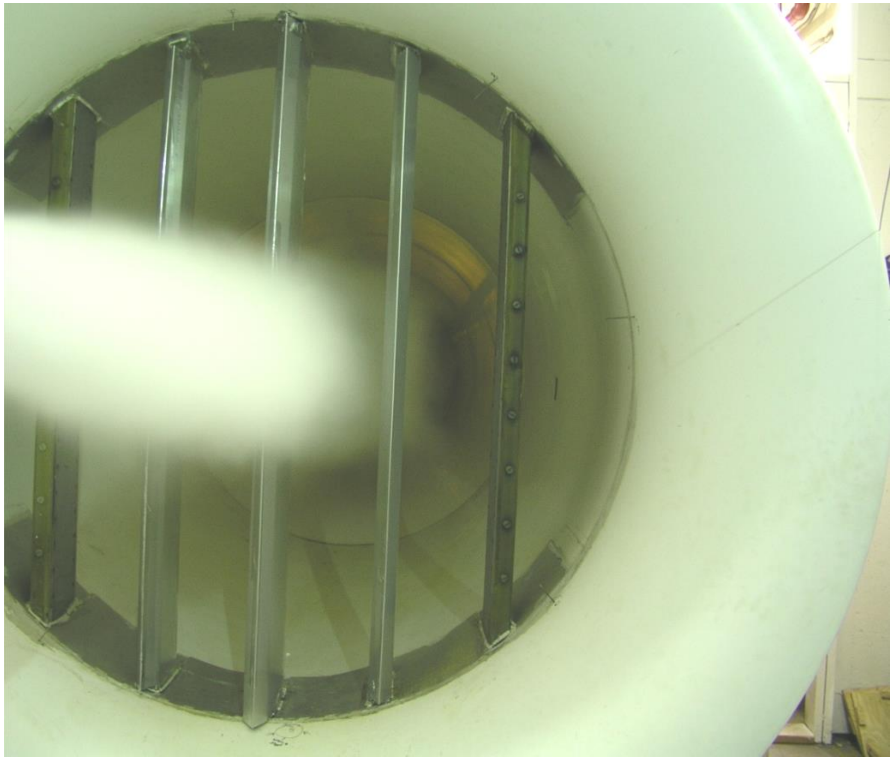
- In flight, the accretion eventually formed a rough ridge at the top and bottom of the cylinder, at the TE of the accretion
- This became very apparent at T=51981, ~6 minutes after the initial even accretion was observed
- The tunnel side view also shows the TE of the accretion getting rougher where it is also very apparent ~6 minutes after the initial even accretion was observed
- This shows good agreement between the tunnel and flight accretion characteristics providing further confidence in the similitude



Comparison of flight F06-1 round bar (top) to airfoil accretion TP883 (bottom) showing higher roughness towards the TE of the accretion

Snow maker in our larger icing tunnels

- The current system was developed in a small icing tunnel
- Our larger tunnels use the same ice crystal icing systems allowing multiple snow maker systems to be installed
- An example is our test cell 5 (TC5), sea level, up to 150 m/s, ~75 cm diameter, ~130 kg/s airflow
- LWC:
  - 0.2 to 5 g/m^3
  - MVD: 15 to 50 microns
- IWC (ICI or blowing snow):
  - 0.1 to 5 g/m^3
  - >15 g/m^3 into engine core by adjusting multiple ice injection guns
  - MVD: 100-700+ microns
- Falling snow (using an area of 70x70 cm as specified by the Ice Genesis requirements):
  - 0.1 to 1.2 g/m^3 @ 40 m/s
  - MVD: 1.0 to 2.5 mm, wet or dry, 60+ minutes
  - MVD: 2.5 to 4.0 mm, wet snow, ~15 minutes
  - Dry to very wet (slush): 0 to >7 vol% water



TC5 inlet with jet injecting ice particles (e.g. blowing snow) and vertical spray bars for liquid water

Adding the NRC snow maker system produces a falling snow test environment

THANK YOU

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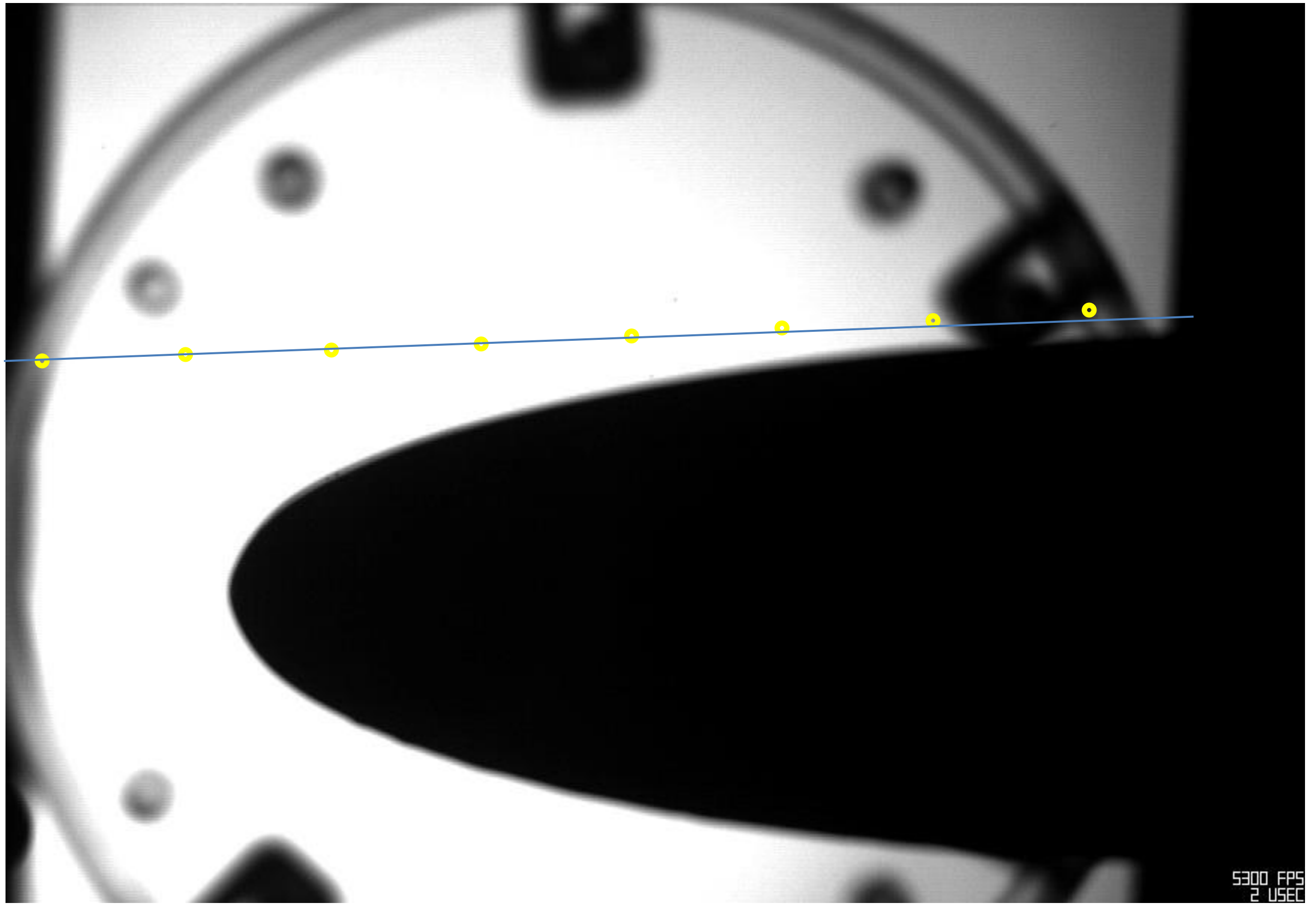
Aerodynamic Deflection

- High-speed video was used to track particles moving over NACA0012 airfoil test article, t=5 cm
- Particle (≈0.5 mm dia.) can be seen to be deflected upwards due to airfoil
- This demonstrates the particle's high drag to mass ratio as seen with snow flakes
- Tunnel conditions: 40 m/s, sea level, TAT=+2^{o}C



Particle surface collision and breakup

- Video of particles bouncing off and some breaking up
- Similar to results seen by Louis Reiter (TUDA) where higher velocity impacts of snowflakes result in very small particles in debris field
- Tunnel conditions: 40 m/s, sea level, TAT=+2°C