Natural-Like Snow Conditions in RTA and NRC Icing Wind Tunnel

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Introduction

Limited capabilities for **falling snow** in IWTs currently exist

Atomizing spray nozzles or ice block grinding systems → mixed phase, high-altitude ice crystal icing conditions or blowing snow

Do not sufficiently match natural falling snow properties in terms of size, morphology and density

ICE GENESIS → improve experimental snow simulation capabilities

The available regulatory, research and guidance documents define approximations of snow conditions but very limited information is available

Temperature range of -4°C to +1°C

Visibility criterion of 0.40 km (¼ mile) → TWC of about 0.9 g/m³

Focus on **falling wet and dry snow** conditions at this temperature range

Ground measurement and **flight test campaigns** (with an ATR-42 aircraft) performed within ICE GENESIS provided much more detailed information on natural-like snow conditions → used as a reference for the artificial snow

SNOW FALL Technology: DEVELOPMENT

- **Prototype 1** in the **RTA** Climatic Wind Tunnel (CWT)
  - Uniformity investigations with **ICCs** and Laser
  - Snow accretion tests on cylinder
  - Particle size measurement with **PIP (DLR and CNRS)**
  - Successful **TRL2** (2019) and **TRL3** assessment (2020)

- **Prototype 2** built in 2021 at **IAG**
  - Wider and larger snow cylinder
    - Width of 940 mm (instead of 450 mm)
  - Wider outlet region
    - To increase width of uniform snow cloud
    - Improved outlet region heater layout
  - Housing over full width of test section
  - Adjustable injection height
  - Successful **TRL4** assessment in 2022

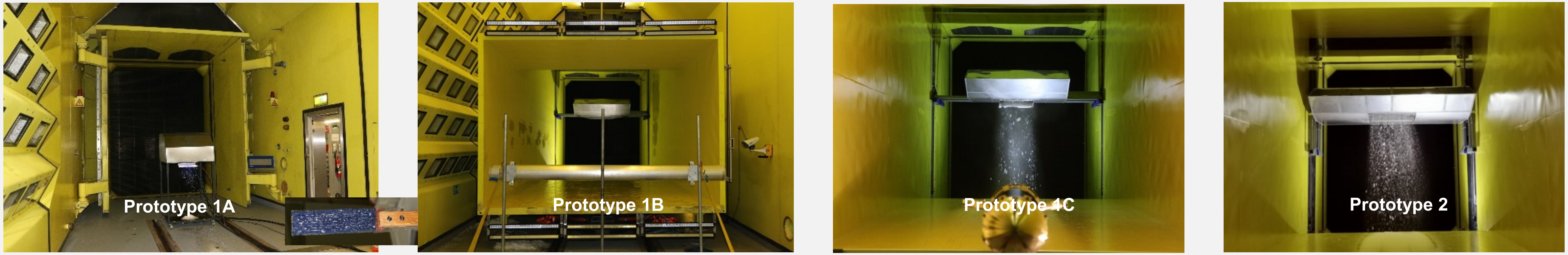


Fig.: Prototype 1 to 2 development / investigations in the RTA Climatic Wind Tunnel (2019, 2020, 2021 and 2022)

NACA0012 Snow Accretion Tests

NACA0012 common test object

Designed and manufactured by the National Research Council Canada (NRC)

Span: 100 mm

Chord: 377 mm

Heated LE region with Type-T Thermocouples

Placed in center of “snow cloud”

PIP and **ICC** measurements in parallel

Camera to record snow accretion process

Accretion shape and growth rate

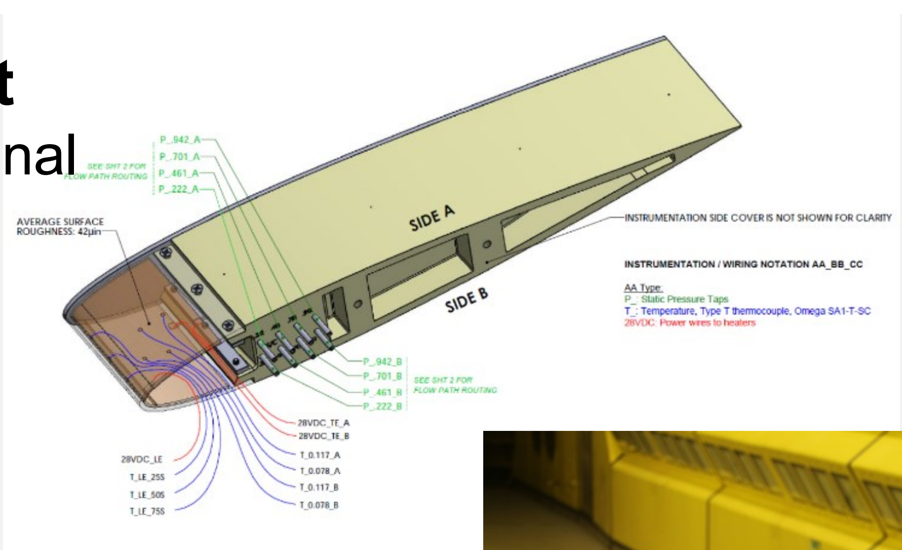


Figure 10: Schematic of NACA0012 test article, provided by NRC

Figure 11: Test setup of the NACA0012 accretion tests, PIP (left), test article and ICCs (center) and camera (right)

Results

- **Dry snow (SF160)**

TAS: 40 m/s
SAT: -3.0°C
AoA: 0.0°
MMD: 617 µm
TWC: 0.33 g/m³
Duration: ~ 10 minutes
Unheated

- No significant snow accretion
- Only about a 1 mm thick layer at stagnation
- Opaque white appearance but was not as solid as an ice accretion created with supercooled liquid water

Figure 12: Photograph of snow accretion on NACA0012 airfoil, RUN7 - dry snow (SF160) at 40 m/s

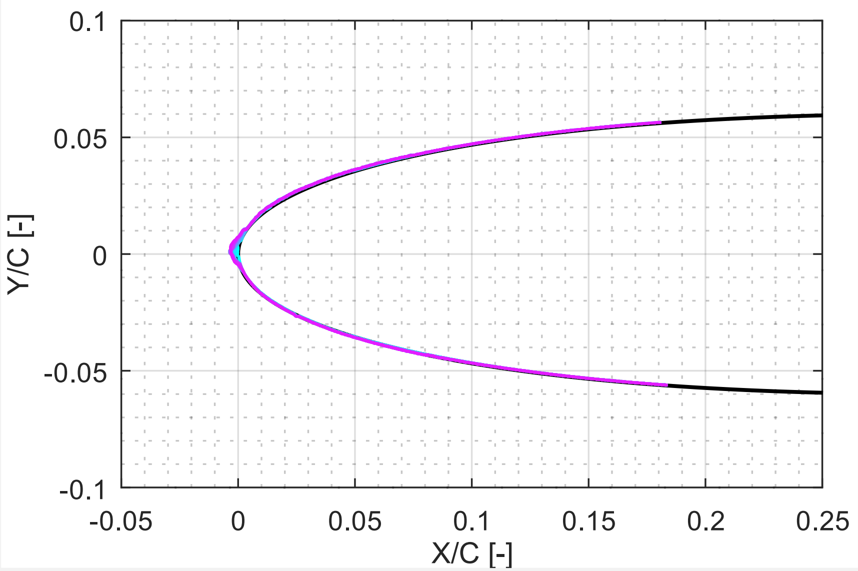


Figure 13: Digitized snow accretion for RUN7 - dry snow (SF160) at 40 m/s

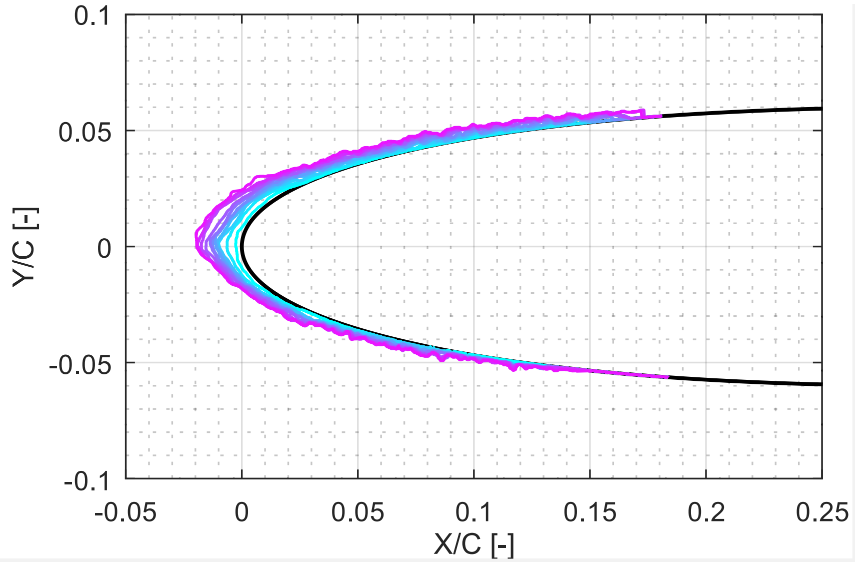
Results

- **Wet snow (SF480)**

TAS: 40 m/s
SAT: -3.0°C
AoA: 0.0°
MMD: 699 µm
TWC: 0.71 g/m³
Duration: ~ 10 minutes
Unheated

Figure 16: Photograph of snow accretion on NACA0012 airfoil, RUN9 - wet snow (SF480) at 40 m/s

- Snow accretion with maximum thickness of 7.5 mm (growth rate of 0.53 mm/min)
- Similar color and opaqueness compared to the medium snow condition, but even softer and a bit less grainy, almost slushy
- Impingement limits slightly further back



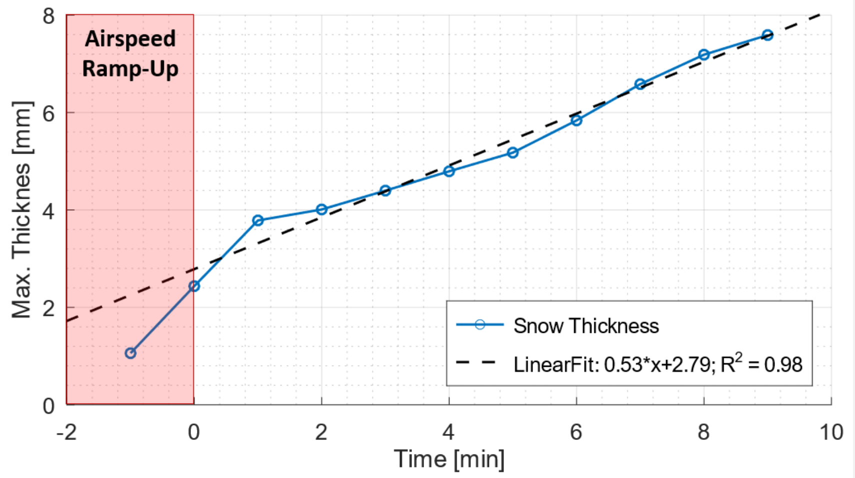
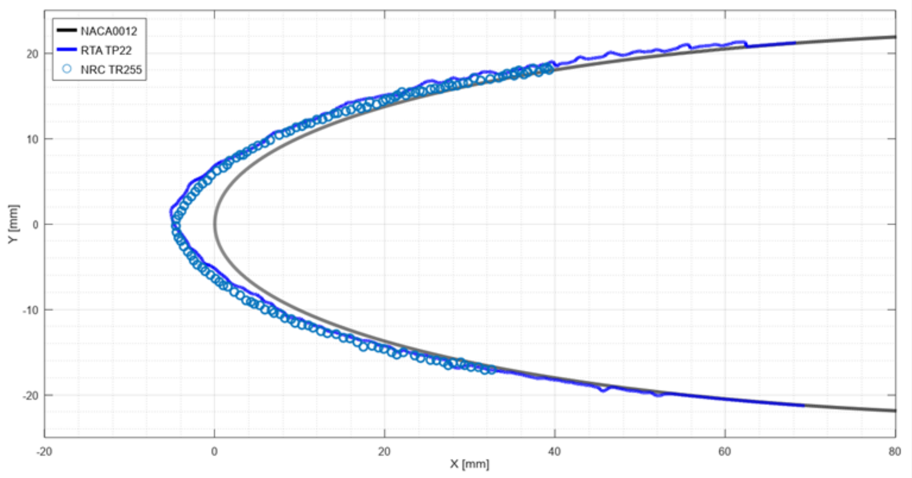
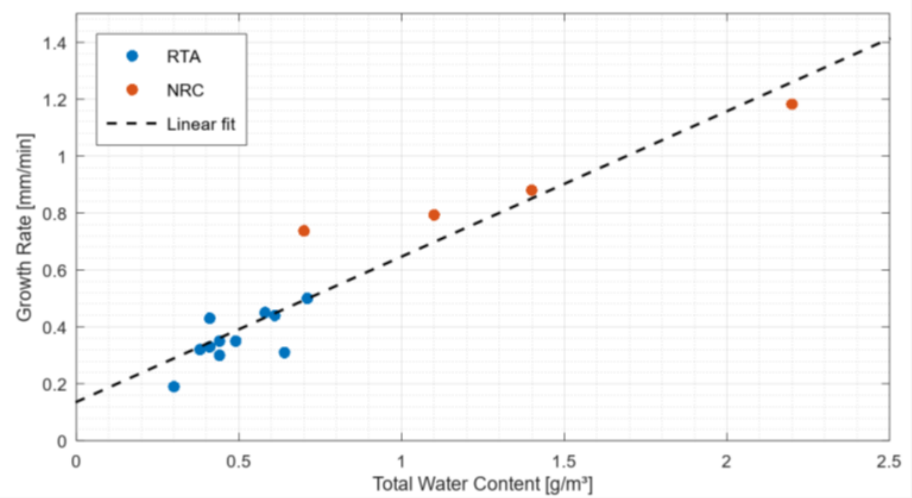


Figure 17: Digitized snow accretion (top), and growth rate (bottom) for RUN9 - wet snow (SF480) at 40 m/s, the colour gradient represents the time step progression of the accretion from light to dark blue.

Comparison of falling snow generated at RTA and NRC through snow accretion tests on NACA0012 common test object

- In order to scale the conditions, the **TWC * Exposure duration** was matched as close as possible (NRC provided accretion photographs every 2 minutes)
  - **NRC TR255**
    - TAS: 40 m/s
    - SAT: -0.3 °C
    - MVD / TWC: 2000 µm / 2.20 g/m³
    - Duration: 120 s
    - TWC*duration: 264 gs/m³
  - **RTA TP22**
    - TAS: 40 m/s
    - SAT: -0.8 °C
    - MVD / TWC: 2180 µm / 0.41 g/m³
    - Duration: 600 s
    - TWC*duration: 246 gs/m³
- **Results show good agreement in impingement limits, thickness, shape and TWC growth rate.**





Conclusion

- Using the **'SnowFall'** technology in the **RTA IWT** it was possible to generate **falling snow** conditions close to the nature
- Detailed **requirements** were derived from ground measurements and flight tests in actual snow conditions and an extensive calibration campaign was performed to characterize the achievable conditions[1)].
- **Snow accretion** tests on a small **NACA0012** wing section were performed to assess the accretion characteristics of different snow types.
  - Snow accretions are very different compared to liquid icing conditions, no runback ice or horn ice formation as well
  - Different accretion characteristics from dry to wet snow
  - The structure was grainy, soft and almost slushy at wetter
  - The generated data will be used to improve and validate the numerical capabilities
- **Intercomparison** between different facilities and flight test data was good

[1)] Breitfuß, W. et al. 'Experimental Simulation of Natural-Like Snow Conditions in the Rail Tec Arsenal (RTA) Icing Wind Tunnel', in. SAE International Conference on Icing of Aircraft, Engines, and Structures, Vienna, 2023; Available at: https://doi.org/10.4271/2023-01-1407

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

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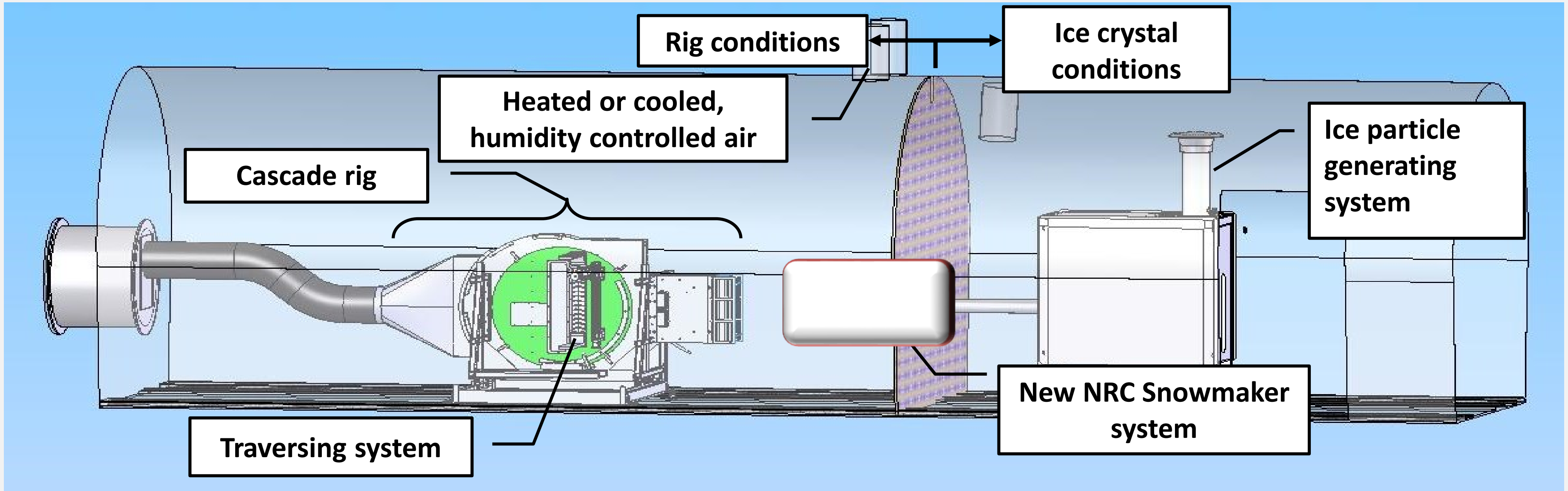
NRC snow maker installed in the Research Altitude Test Facility (RATFac)

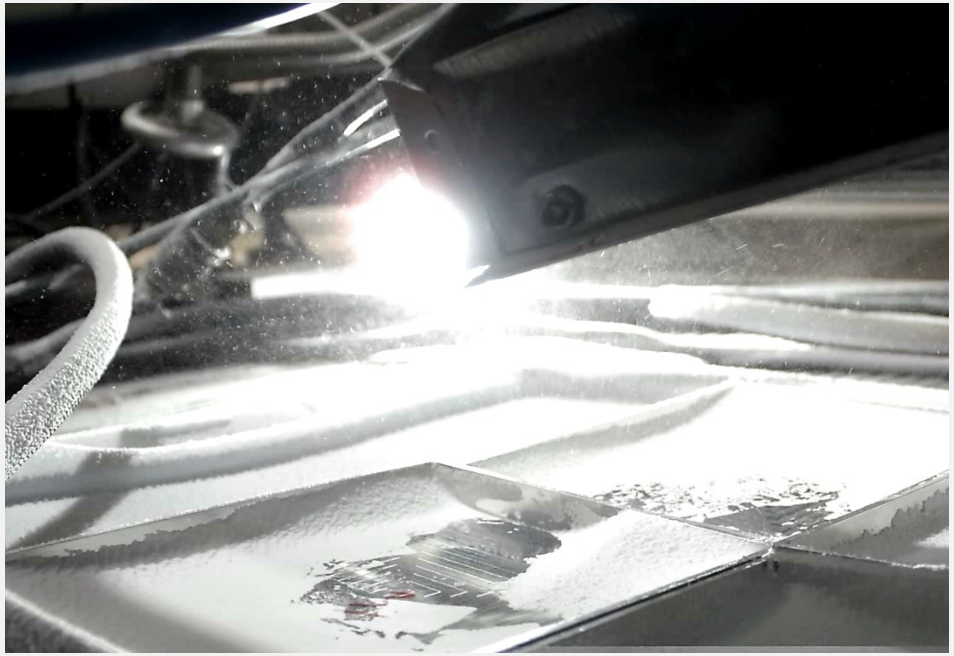
- Flow through facility, i.e. no recirculation
- Cascade rig has ice crystal icing instrumentation ideally suited for snow, temperature, pressure, velocity, TWC, all in dry and wet conditions
- Operating range based on 13 x 25 cm cross-section

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



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 for large particles and low total water content (TWC)
- Summary of falling snow envelope achieved in cascade rig in RATFac:
  - TWC: 0.2 to 2.5 g/m^3 (V_tunnel=40 m/s)
  - Dv50*: 1 to 3 mm (4 mm possible for wet snow)
  - 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: <1 to 60 minutes
  - Met all uniformity and repeatability requirements from calibration specification, Deliverable 7.1
  - TRL5 achieved



Snow being collected for bulk density measurement
T= -5^{o}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

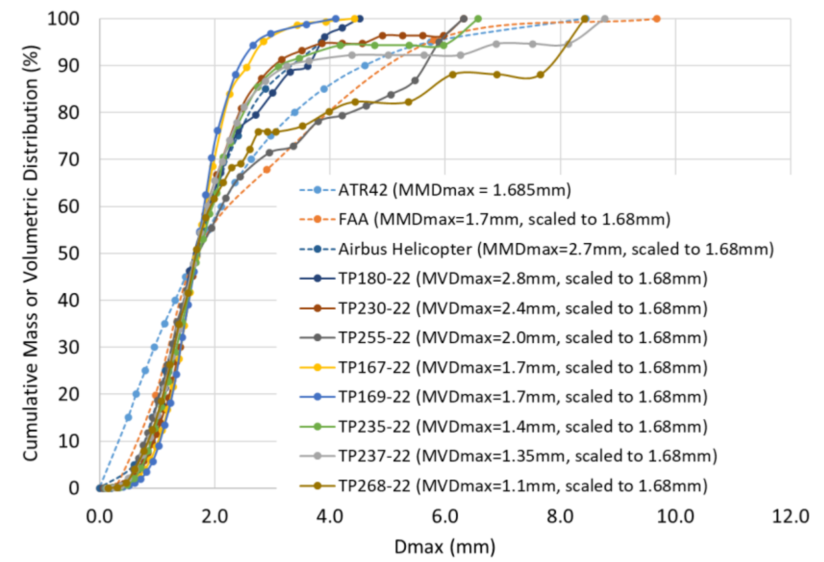
** Natural snow is 34 to 720 kg/m^3 with dry snow typically below 200 kg/m^3 : “Szilder, Krzysztof, Snow accretion prediction on an inclined cable, 2019.

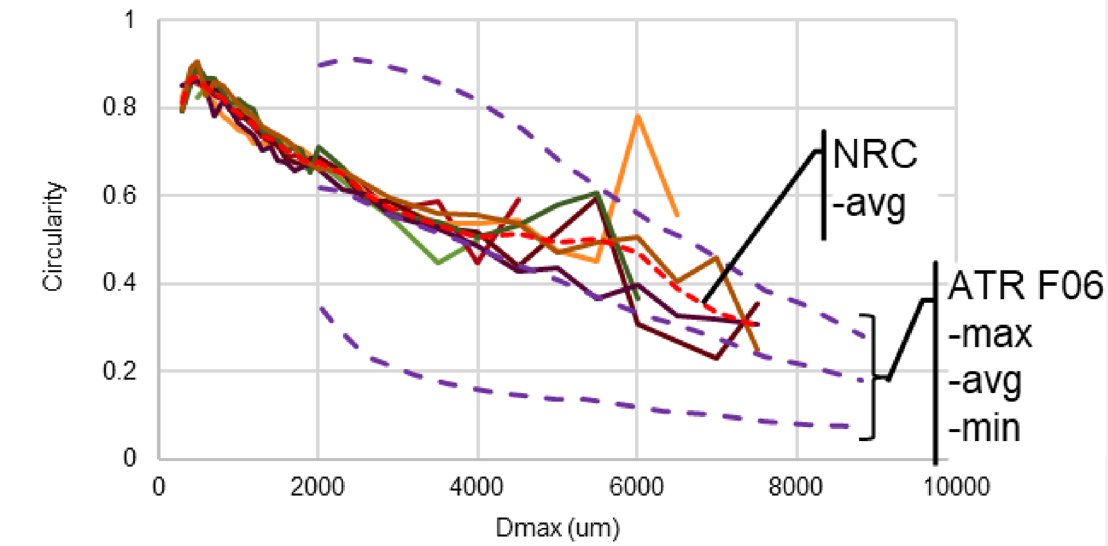
Particle surface collision and breakup

- Video of particles bouncing off and some breaking up
- Similar to results seen in the Ice Genesis project where higher velocity impacts of snowflakes result in very small particles in debris field
- Tunnel conditions: 40 m/s, sea level, TAT=+2^{o}C

Falling snow particle characteristics

- Although MVD is used as a defining parameter for particle size, the distribution is also of interest
- A range of NRC snow maker test point MVDmax's* are scaled to the average ATR42 flight data, MMDmax=1.7 mm
- Results show excellent agreement with the reference data sets where there is only a small difference in the 1 to 2 mm size range and only with the ATR42 flight data
- Repeat points (235 and 237) are in excellent agreement showing good repeatability
- MVD for Deq had good overlap: Tunnel 0.9-2.4 mm versus flight 1.8-3.9 mm
- Tunnel particle circularity (α area/perimeter^2) characteristics closely match ATR42 flight F06 rimmed aggregate data in magnitude and trend

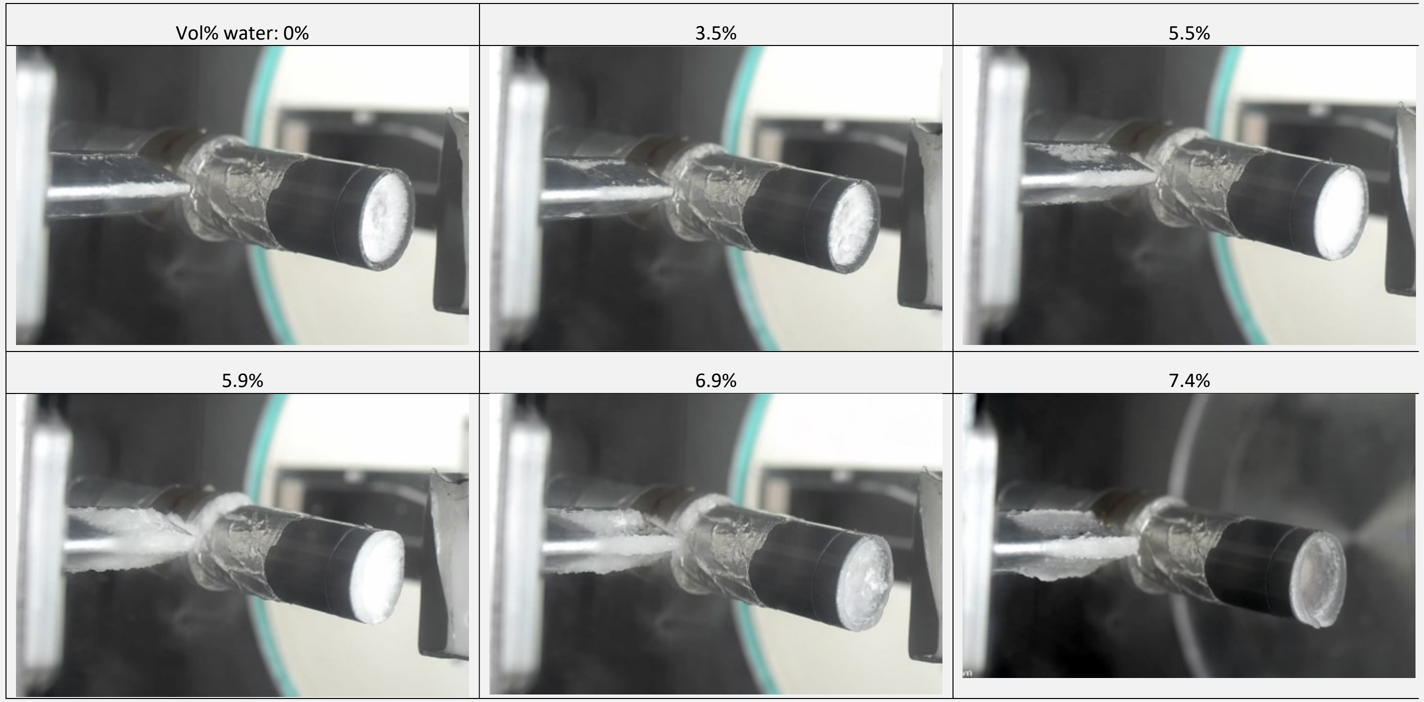




* Since the snow maker particle density is unknown, volumetric measurements are the only comparable option

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 published water percolation observations*

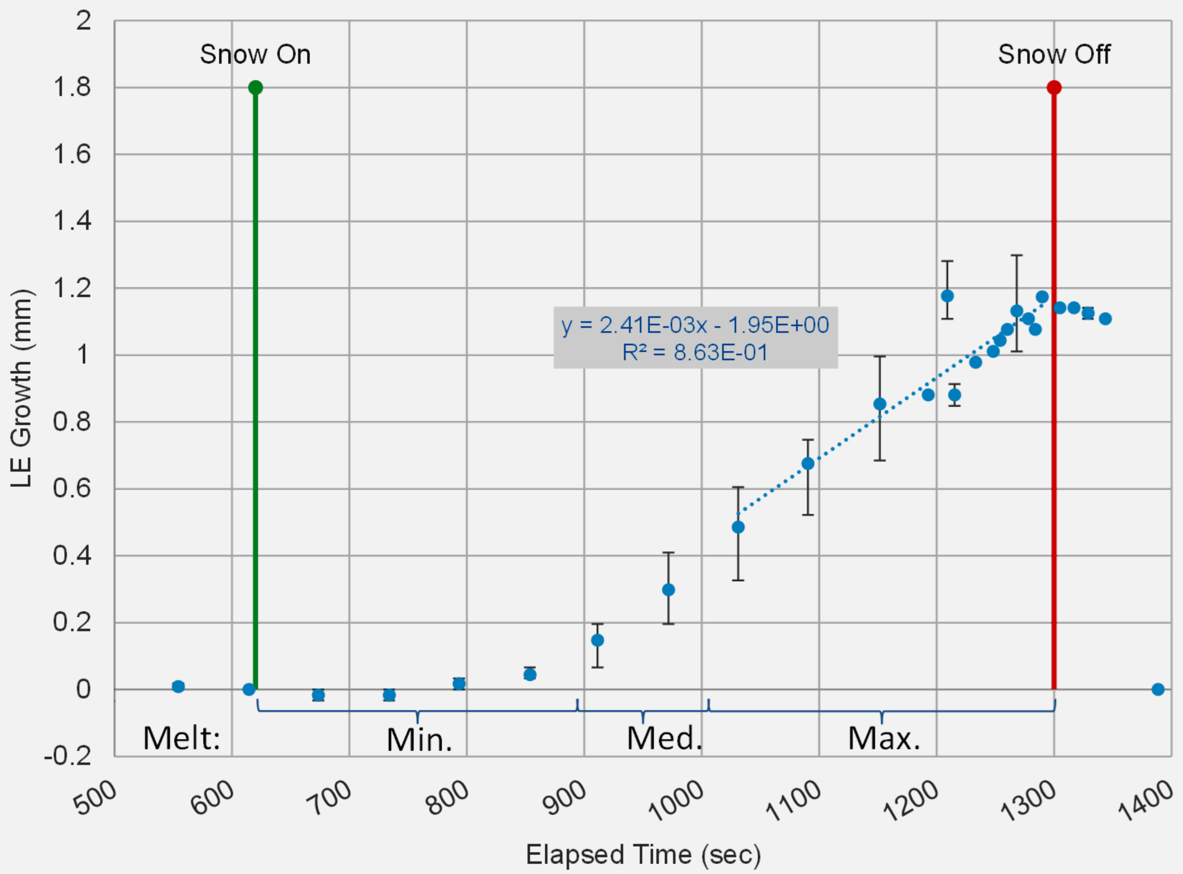


Images of increasing vol% melt measured by the NRC Ice Property Probe (IPP)

*Ebner et al, Liquid-water content and water distribution of wet snow using electrical monitoring, Cryosphere Discussions, 2020

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



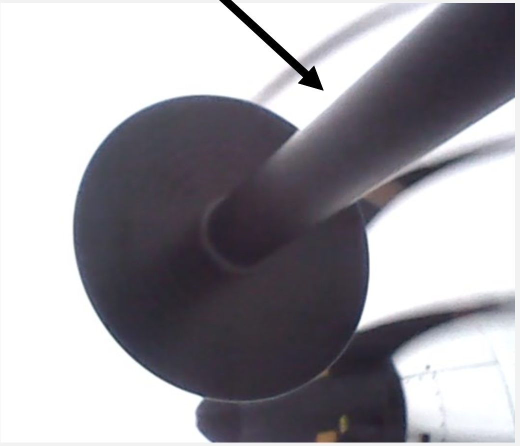
Leading edge ice growth rate for TP876-21
Error bars are min and max based on resampling 3 times

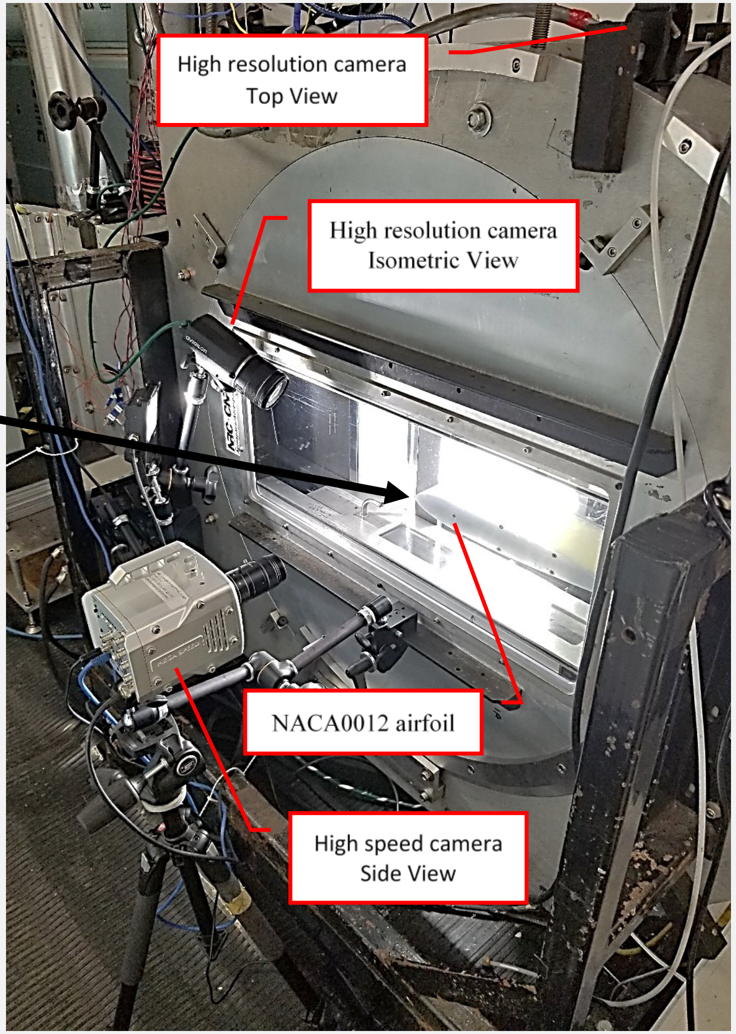
Artificial snow accretion vs. flight

- 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
- Tunnel: NACA0012 airfoil, unheated, AOA=0º
- Flight: Capped cylinder perpendicular to flow on ATR42 flight test aircraft

Test Point	Alt	TAS	SAT	MMD*	MVD*	TWC
	ft	m/s	ºC	mm	mm	g/m³
Flight F06-1	5966	81	-1.9	1.34	NA	0.24
Tunnel TR883-21	5966	82	-2.2	NA	2.04	0.21

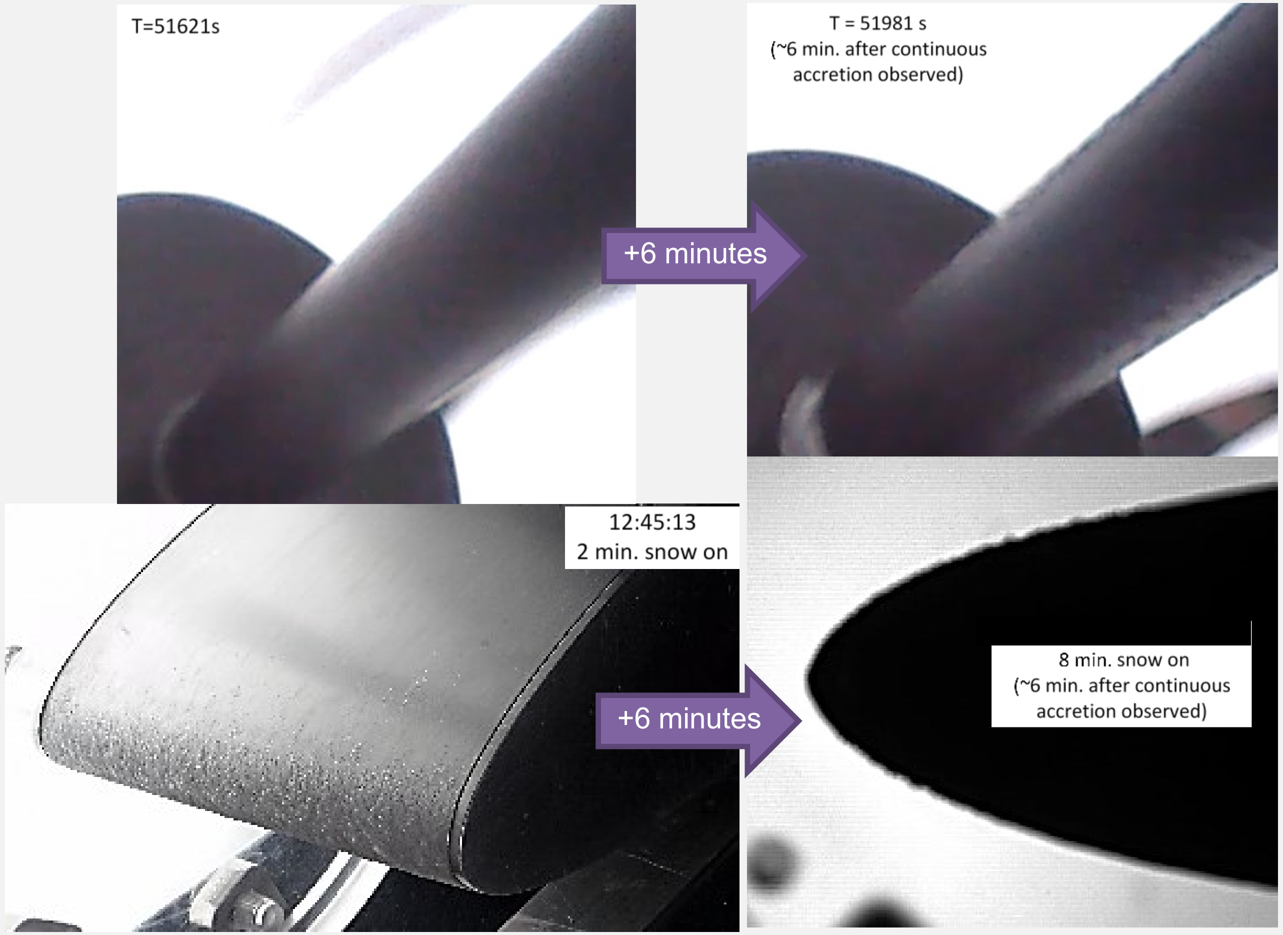
*Based on Dmax





Artificial snow accretion vs. flight

- In flight and in the tunnel, the accretion started with an even coverage with a rough or dimpled surface
- After ~6 minutes, the accretion grew where its trailing edge (TE) was seen to get rougher both in flight and in the tunnel
- This shows good agreement between the tunnel and flight accretion in both rate and morphology providing further confidence in the similitude



Comparison of flight F06-1 round bar (top) to airfoil accretion TP883 (bottom)
Left: Initial accretion, Right: Roughness at accretion TE

Snow maker in larger NRC icing wind tunnels

- The current system was developed in a small icing wind tunnel
- Our larger tunnels use the same ice crystal icing systems
- Therefore, multiple snow maker systems can be installed in the larger facilities
- An example is our test cell 5 (M7-TC5), sea level, up to 150 m/s, ~75 cm diameter, ~130 kg/s airflow

LWC:

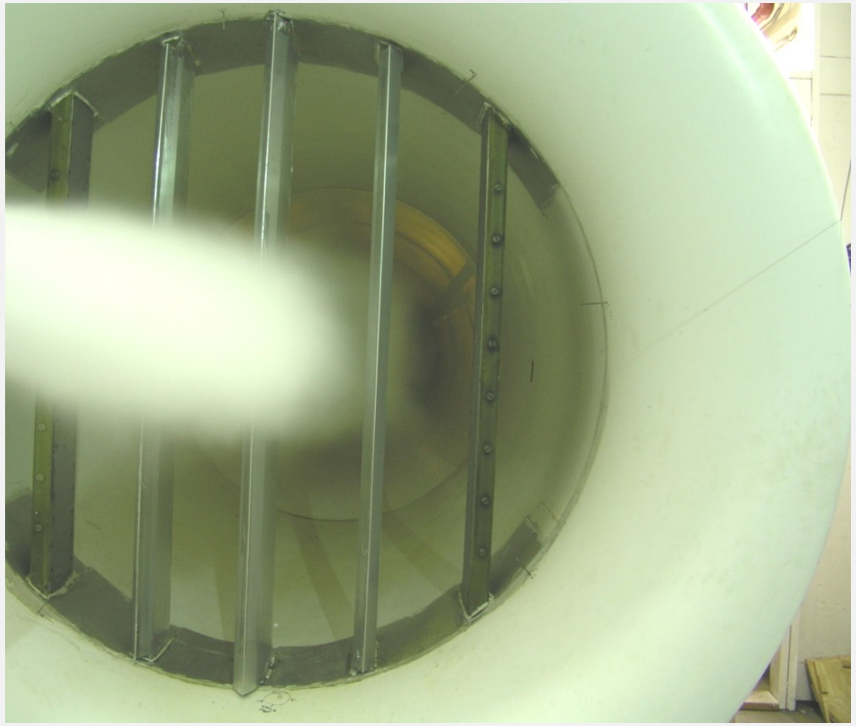
- 0.2 to 5 g/m^3
- MVD: 15 to 50 microns

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 3.0 mm, wet or dry, 60+ minutes
- MVD: 3.0 to 4.0 mm, wet snow, ~15 minutes



TC5 inlet with jet injecting ice particles (ICI, blowing snow) and vertical spray bars for liquid water

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

Way forward

- Current systems at TRL4/5 level
- Next steps to reach TRL6:
  - Upscaling of systems
  - Test on representative industrial configuration
  - Characterization of snow particle density versus size

RTA Icing tests with running helicopter engine

NRC engine icing tunnel

THANK YOU

Hermann Ferschitz (RTA)
Dan Fuleki (NRC)

ICE GENESIS

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