Icing Physics Studies Using the 3D SIDRM Test Article: Aerodynamic and Supercooled Liquid Icing Analysis

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Introduction – Why Study Engine Icing

- Numerous events of power-loss and engine damage since the 1990’s (Bravin, 2019)

- Engine icing (ice crystal icing) studied at NASA (and elsewhere)
  - From full scale engine tests to component level fundamental icing physics studies

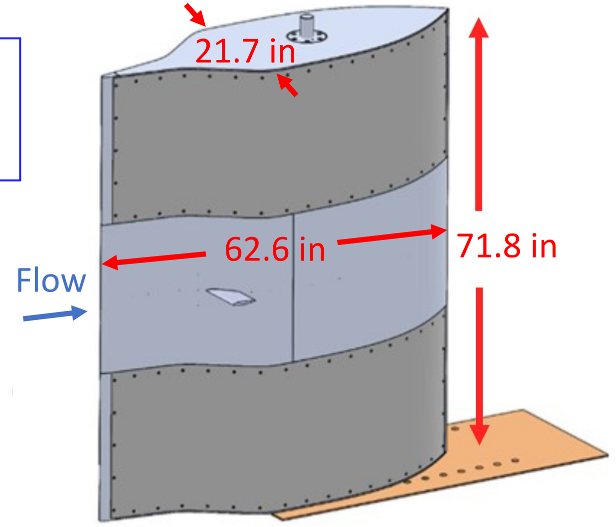
- **Goal**: Gather data to develop and validate computational icing tools to predictively assess the onset and growth of ice in current and future engines during flight, to aid certification

Testing General Details

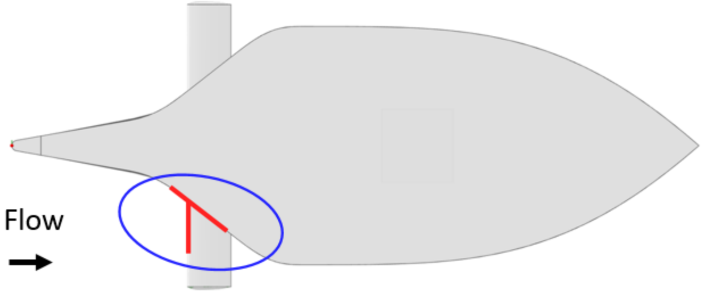
- Conducted icing tests in the NASA Icing Research Tunnel (IRT)
  - Conducted in early 2022
  - Utilized Simulated Inter-compressor Duct Research Model (SIDRM)
    - 3D geometrical features of an inter-compressor duct and strut region of a turbofan engine (curved surface with a strut)
  - 17 days of testing
    - Aerothermal characterization
    - Supercooled liquid icing tests
    - Ice crystal icing tests

- **Testing primary goal**: Generate a set of ice accretions on a 3D test article to provide validation data for engine icing simulation tools like GlennICE

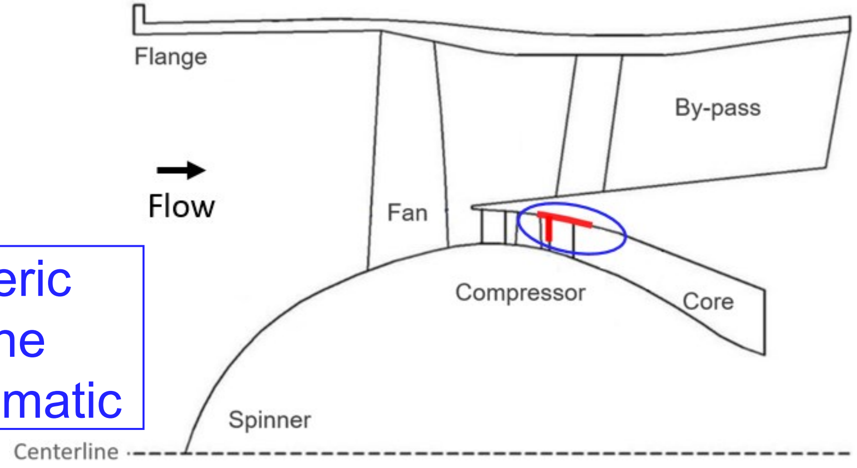
SIDRM schematic



SIDRM profile view

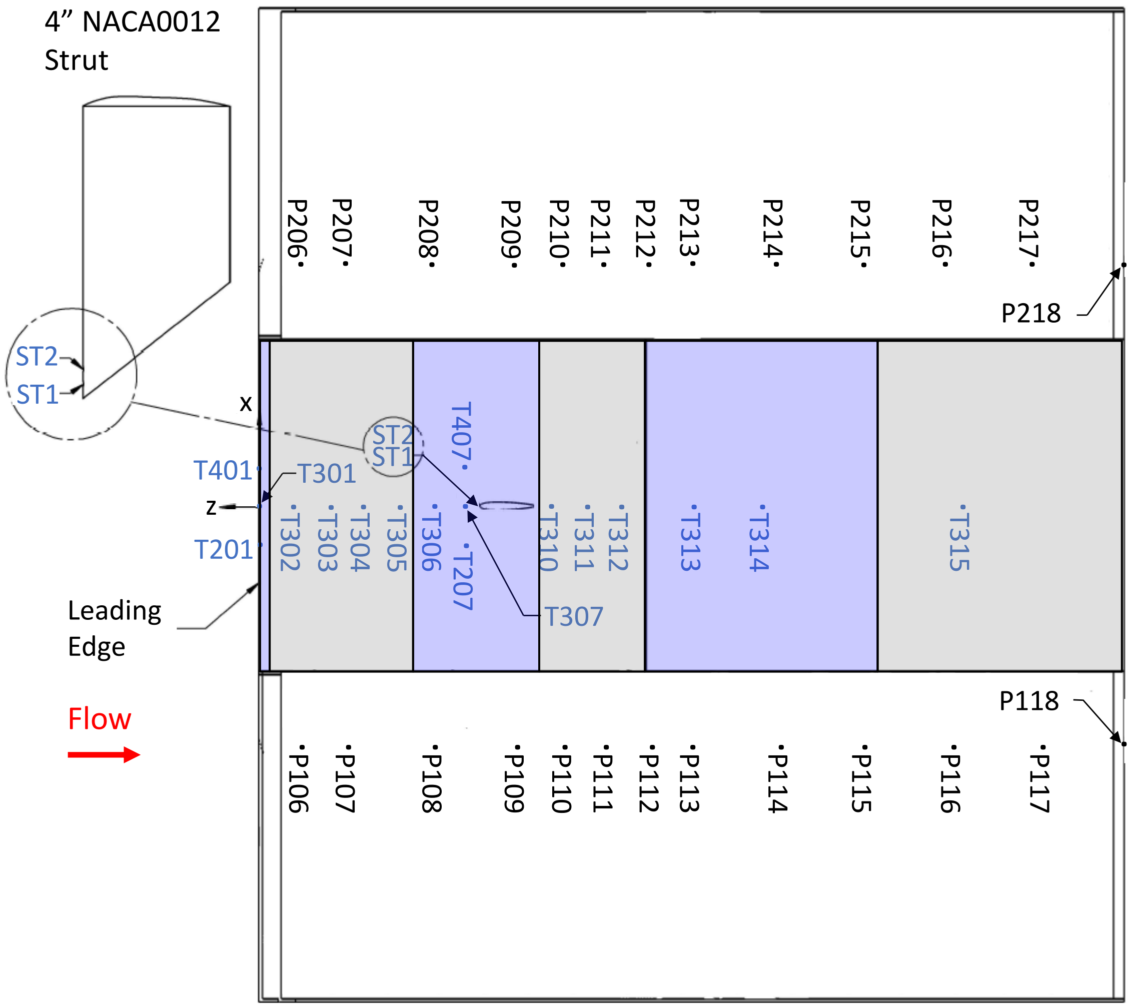


Generic engine schematic



SIDRM Built-In Instrumentation

- 64 Pressure taps
- 43 Thermocouples
- 11 Heat flux gauges
  - Imbedded internally in aluminum main body
- 6 Independently controlled heater zones
  - Beneath main body skin
  - Heaters are symmetric on both sides



View of TCs, pressure taps and heater zones (shaded areas)

Aerothermal Tests

Objective:

- Performed to characterize flow around unique geometry
- Compare against simulation predictions

Measurements:

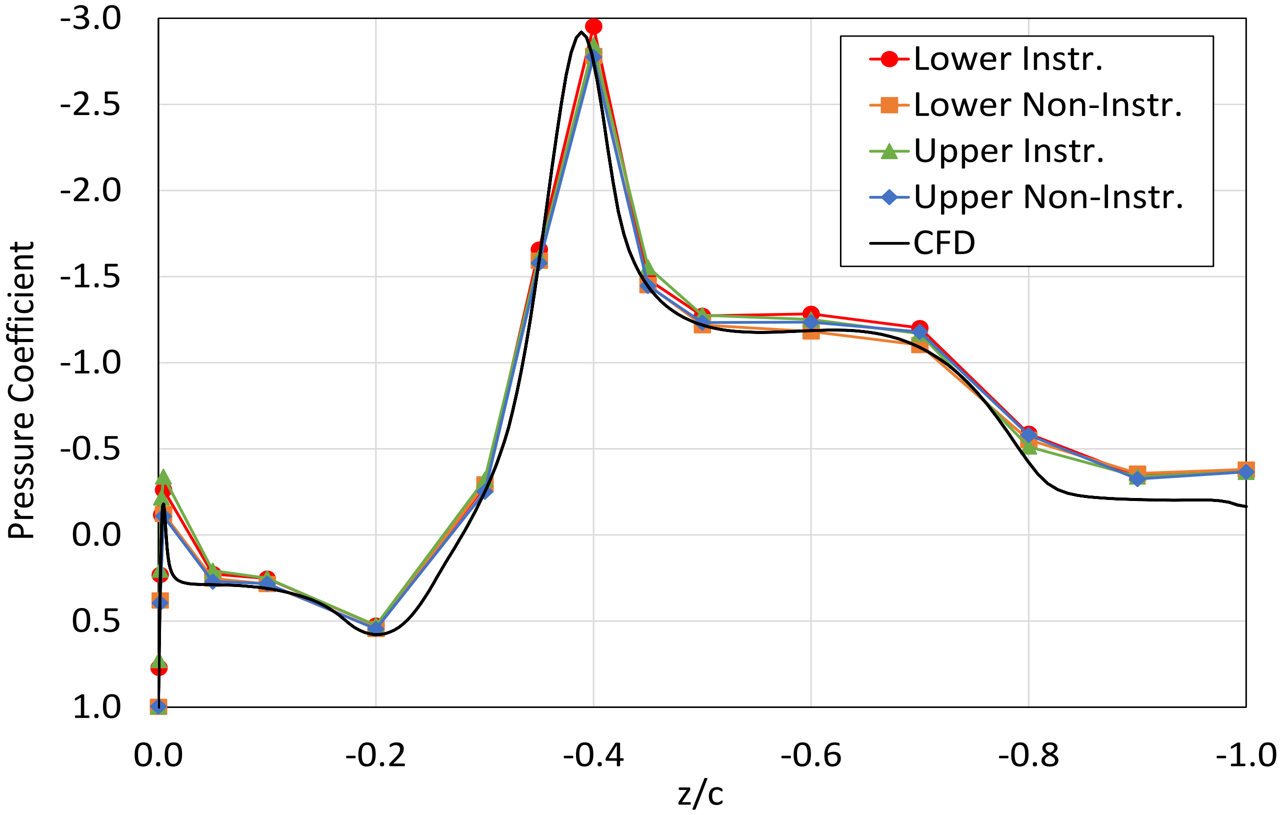
- Pressure taps (comparisons with CFD shown)
- Thermocouples

Test Conditions:

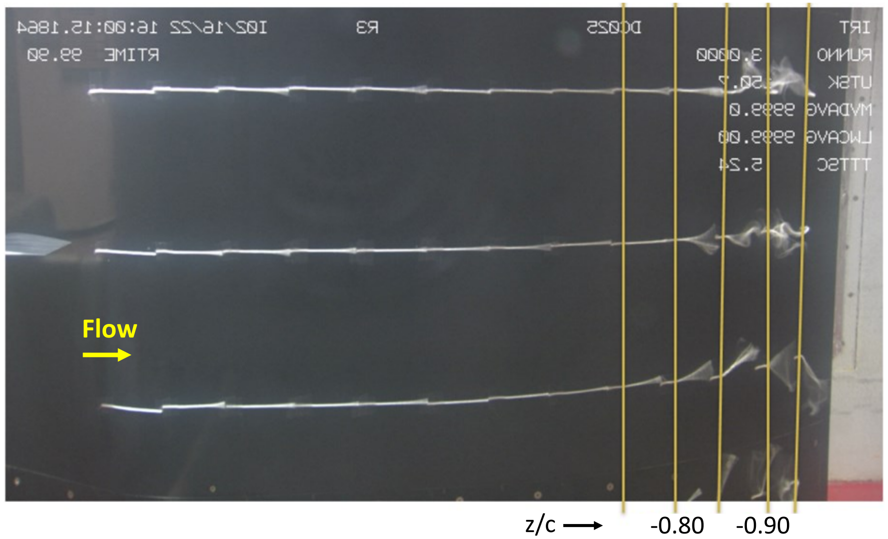
AoA (°)	0	0	0	0	0	1	2	3	4	4	4	4	4
U (knots)	50	100	150	200	230	150	150	150	50	100	150	200	230

Aerodynamic Tests

- Good agreement btw sim and exp
- Tap measurements
  - 4 curves (upper/lower, both sides)
  - Lay on top of each other at AoA = 0˚
  - Flow separation beyond z/c = -0.8
- Ansys Fluent
  - Simulated SIDRM inside tunnel with no slip at SIDRM walls



AoA (°)	0	0	0	0	0	1	2	3	4	4	4	4	4
U (knots)	50	100	150	200	230	150	150	150	50	100	150	200	230

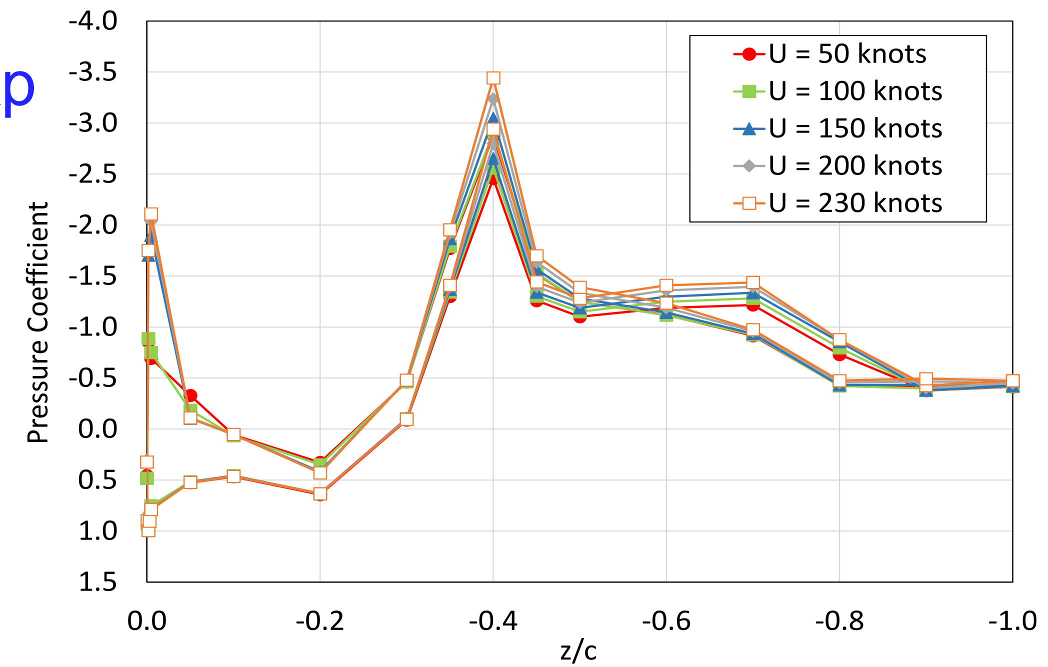


Aerodynamic Tests

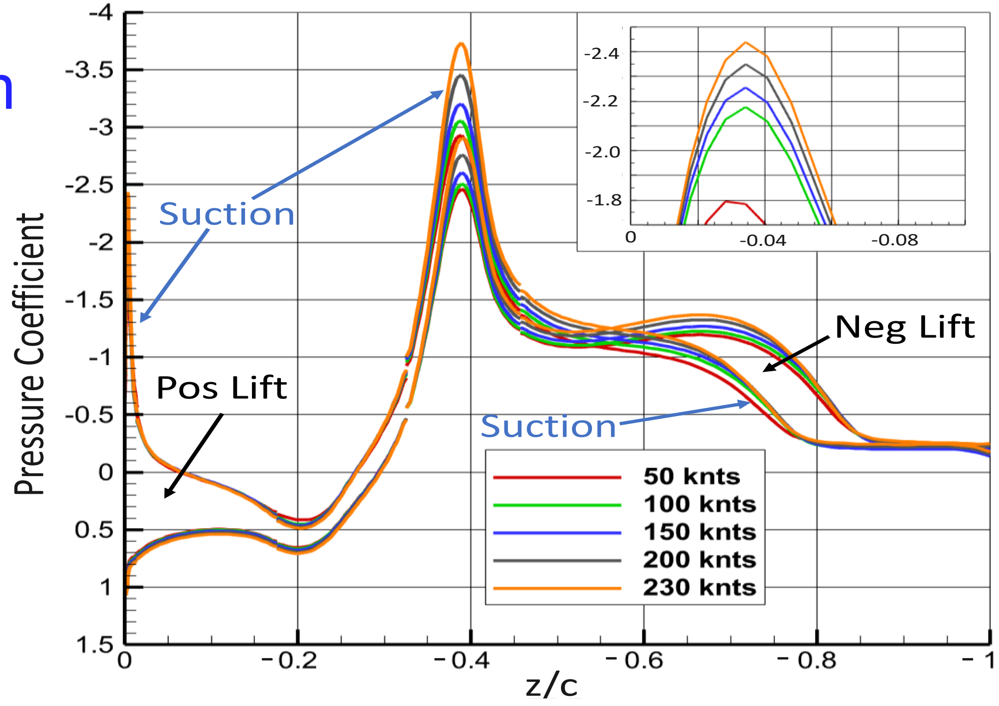
- Good agreement btw sim and exp
- Both capture suction spike near LE
- Both capture Cp spread with increasing airspeed at z/c = -0.4 (Reynolds number effect)
- Negative lift produced in aft half at AoA = 4˚

AoA (°)	0	0	0	0	0	1	2	3	4	4	4	4	4
U (knots)	50	100	150	200	230	150	150	150	50	100	150	200	230

Exp



Sim



Supercooled Liquid Icing

Parameters that impacted:

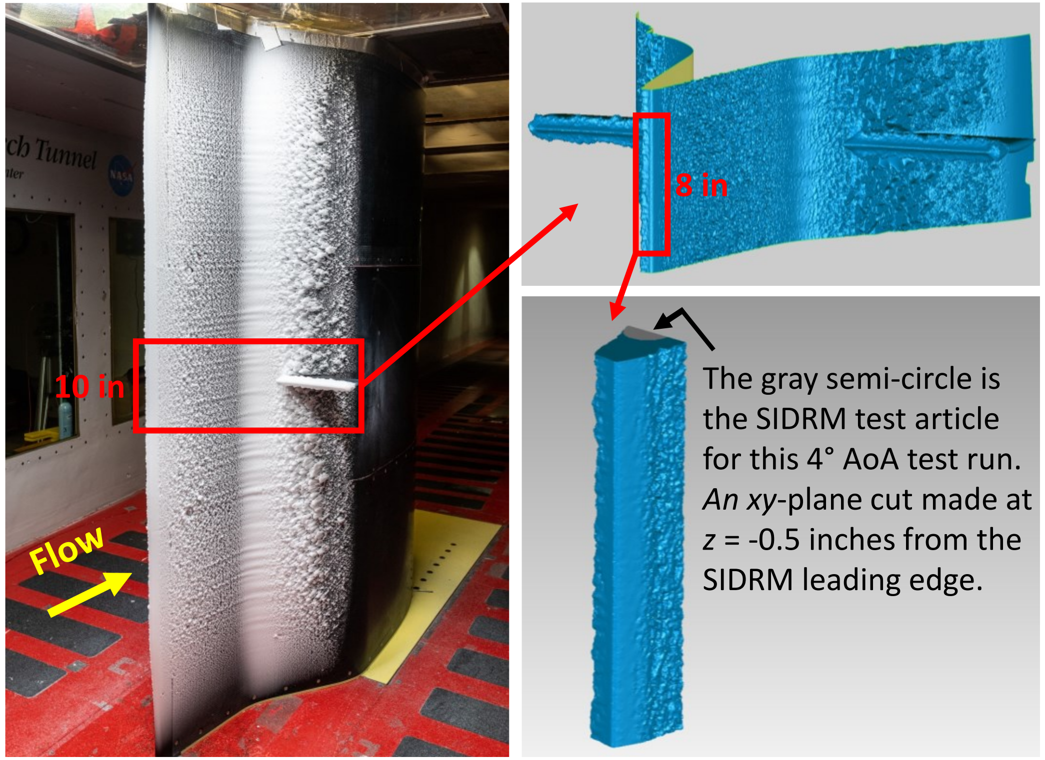
1. Icing size (and mass)
2. Location (icing extent)
3. Characteristics
4. Surface temperature

Parameter Sweeps conducted:

- 3 MVD sweeps
- 1 Total air temperature sweep
- 1 AoA sweep
- 2 Accretion time sweeps

Measurements:

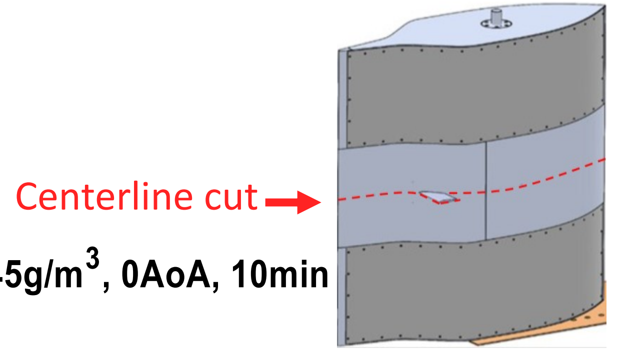
- Ice geometry (3D scanner)
- Ice mass (cut and weigh)
- Surface TCs
- Photo/video



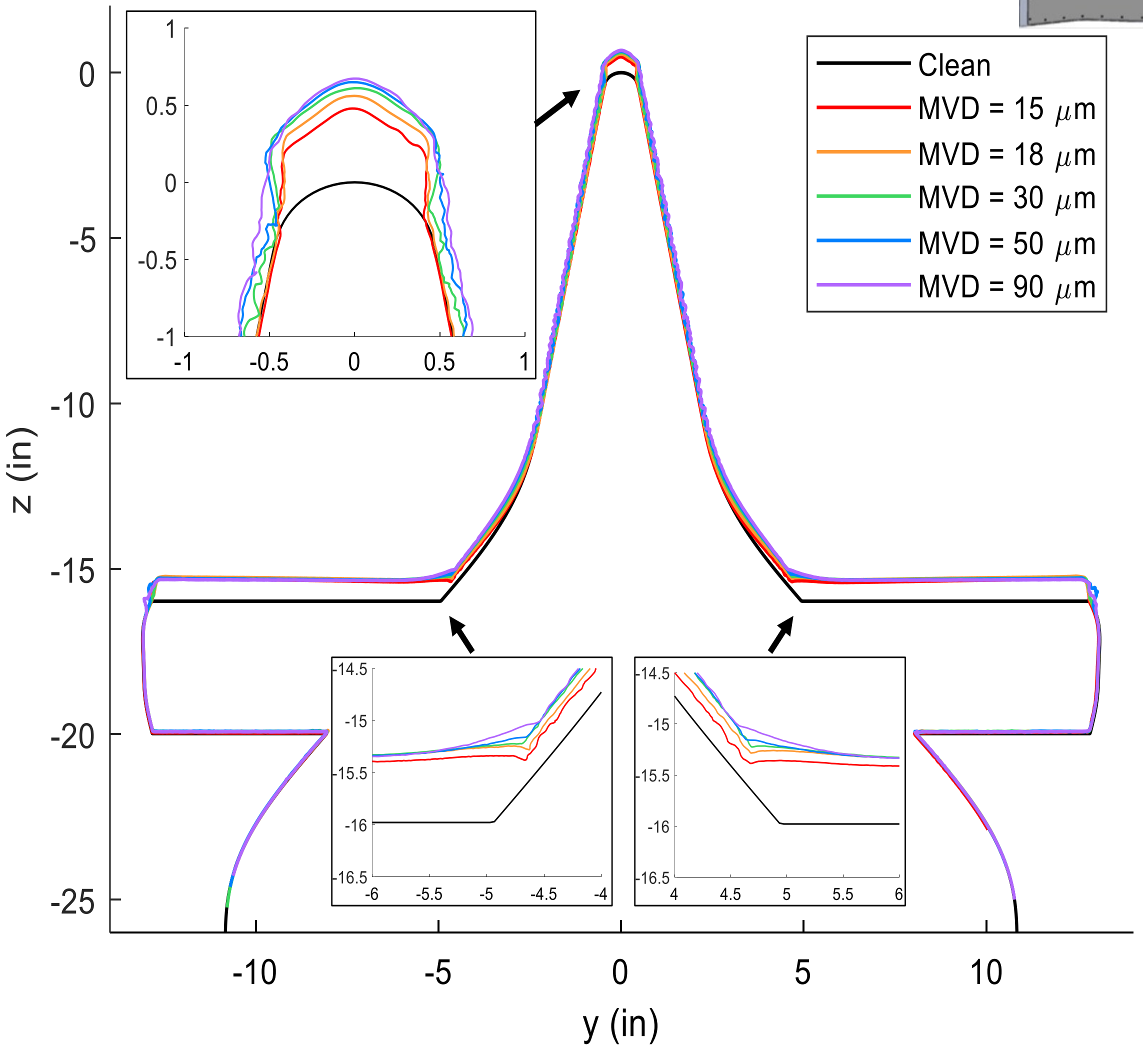
Supercooled Liquid Icing – Size: MVD

- Larger MVD ➔ larger ice accretion
- Larger MVD ➔ more ballistic
- Larger MVD ➔ greater collection eff.

Target Test Conditions						Ice Accretion Measurements		
Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
Accretion Time (min)	T_0 (°C)	U (knots)	AoA (°)	MVD (µm)	LWC (g/m^3)	Both Struts Ice Mass (g)	Main Body Ice Mass (g)	LE Ice Vol. (cm^3)
10	-17	150	0	15	0.45	66	172	56.3
10	-17	150	0	18	0.45	70	221	62.3
10	-17	150	0	30	0.45	79	407	78.8
10	-17	150	0	50	0.45	79	548	87.1
10	-17	150	0	90	0.45	83	781	93.7



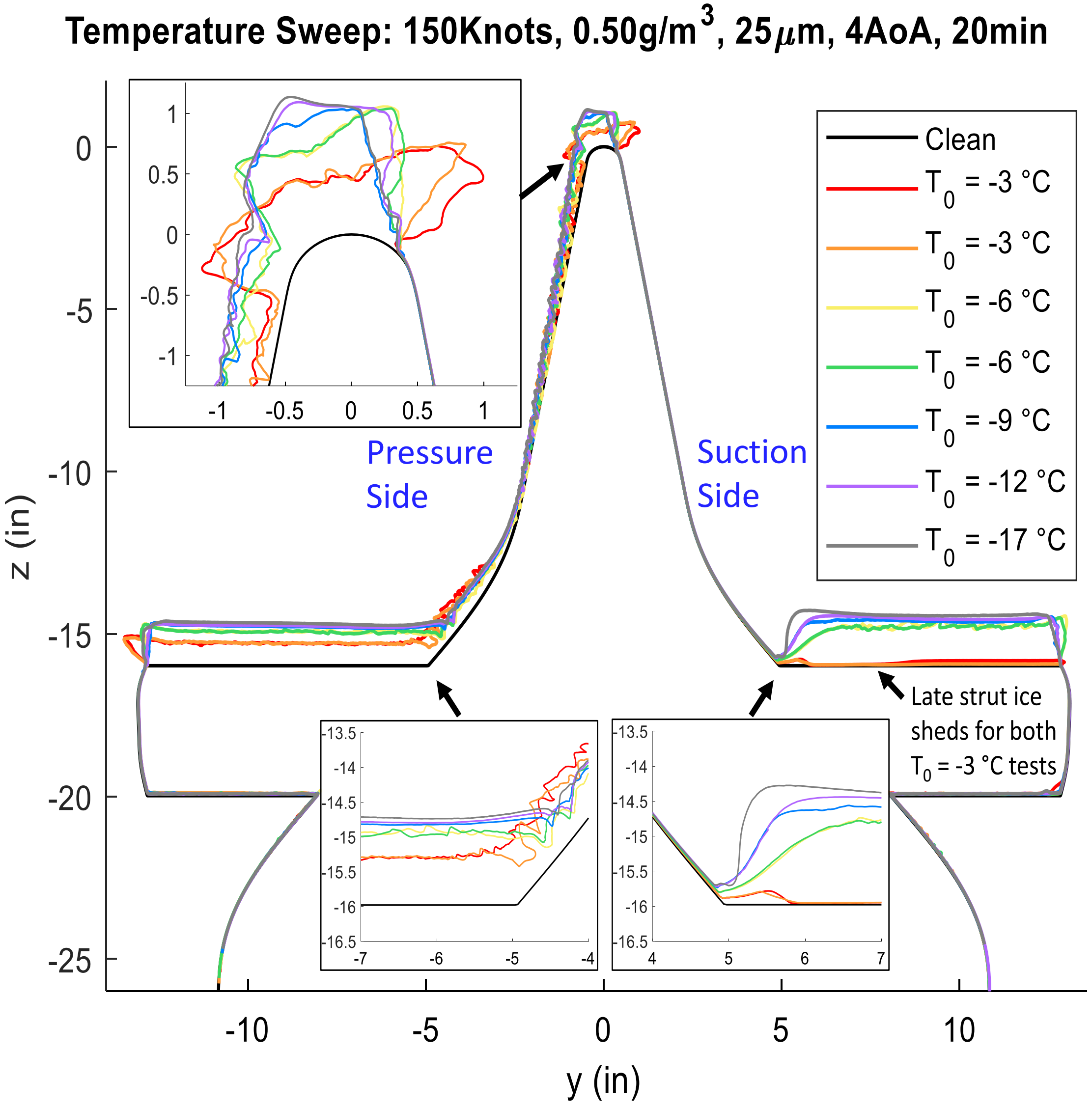
MVD Sweep: -17°C, 150Knots, 0.45g/m^3, 0AoA, 10min



Supercooled Liquid Icing – Size: T_0

- Colder T_0 ➔ larger ice accretion
- Colder T_0 ➔ less feather shedding
- Colder T_0 ➔ Stronger ice cohesion, fewer large feathers experiencing larger drag forces

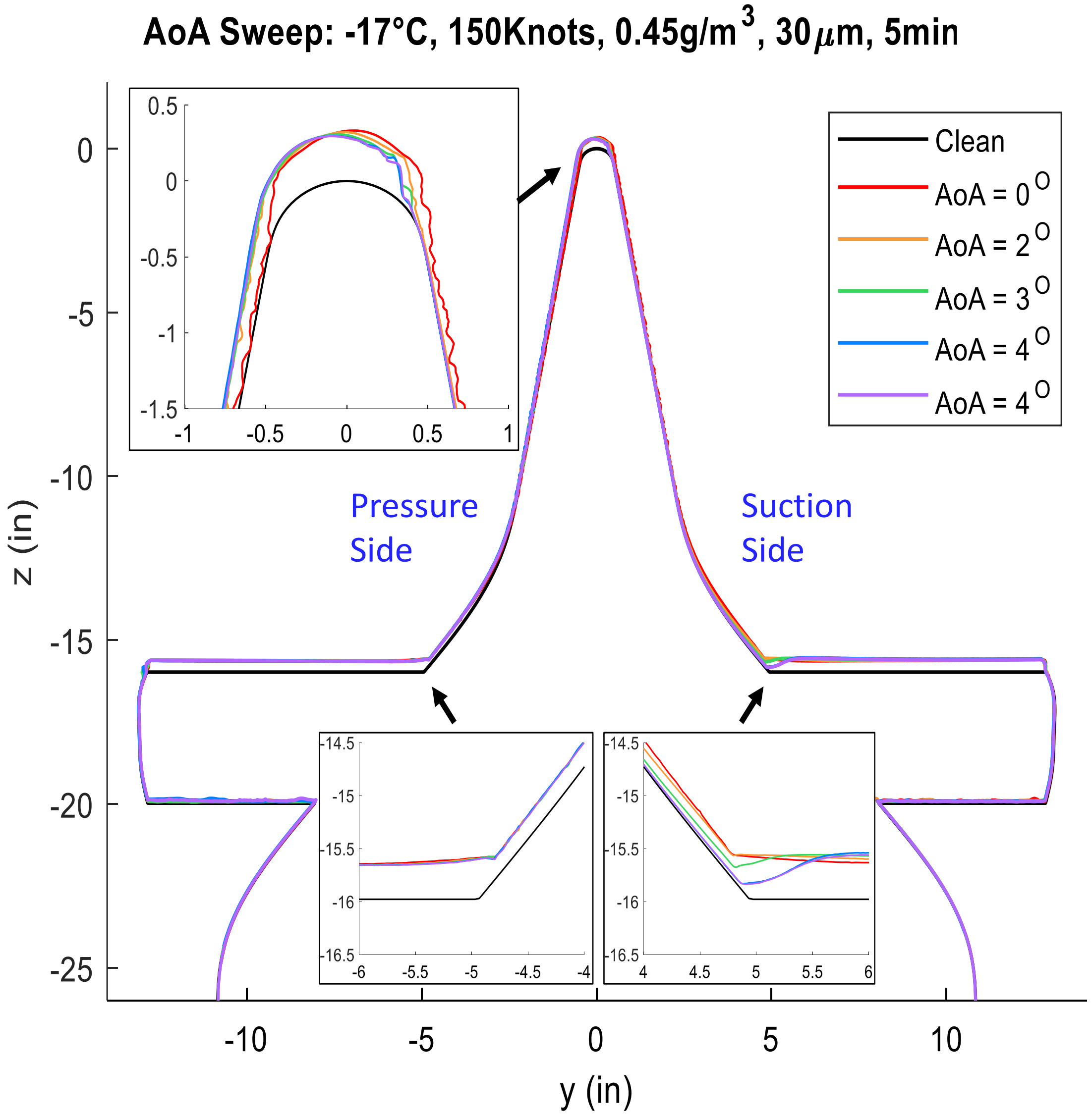
Target Test Conditions						Ice Accretion Measurements		
Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
Accretion Time (min)	T_0 (°C)	U (knots)	AoA (°)	MVD (μm)	LWC (g/m³)	Both Struts Ice Mass (g)	Main Body Ice Mass (g)	LE Ice Vol. (cm³)
20	-3	150	4	25	0.50	139*	395	147.8
20	-3	150	4	25	0.50	132*	393	147.9
20	-6	150	4	25	0.50	247	477	136.6
20	-6	150	4	25	0.50	234	480	137.5
20	-9	150	4	25	0.50	239	526	156.6
20	-12	150	4	25	0.50	238	551	170.0
20	-17	150	4	25	0.50	224	595	172.6



Supercooled Liquid Icing – Size: AoA

- Smaller AoA ➔ larger ice accretion
- Smaller AoA ➔ fewer shadow zones
  - More ice on ramp and strut LE on the suction side

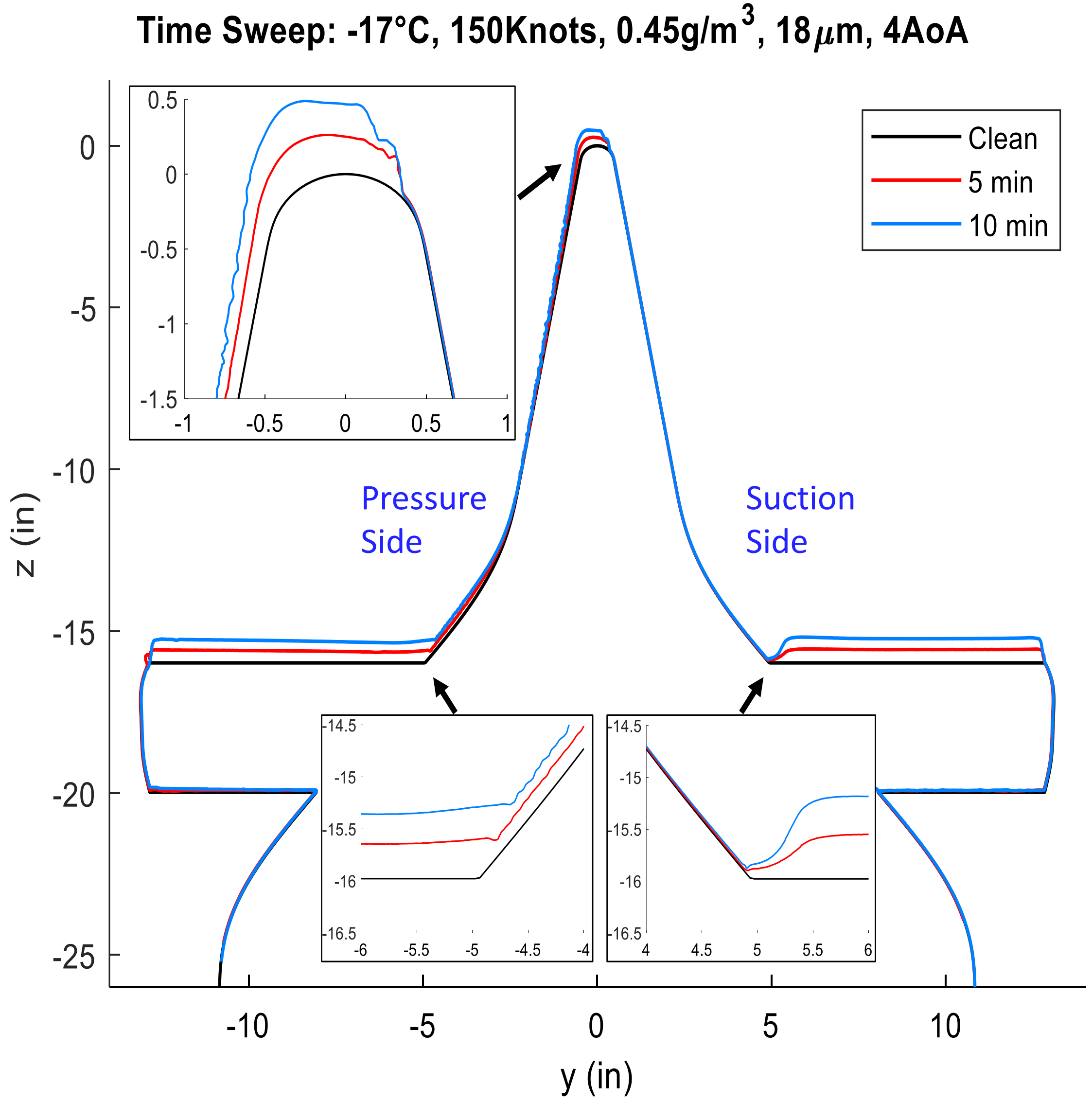
Target Test Conditions						Ice Accretion Measurements		
Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
Accretion Time (min)	T_0 (°C)	U (knots)	AoA (°)	MVD (μm)	LWC (g/m^3)	Both Struts Ice Mass (g)	Main Body Ice Mass (g)	LE Ice Vol. (cm^3)
5	-17	150	0	30	0.45	33	208	43.9
5	-17	150	2	30	0.45	33	205	42.7
5	-17	150	3	30	0.45	35	188	39.8
5	-17	150	4	30	0.45	35	176	40.0
5	-17	150	4	30	0.45	33	184	39.4



Supercooled Liquid Icing – Size: Accretion Time

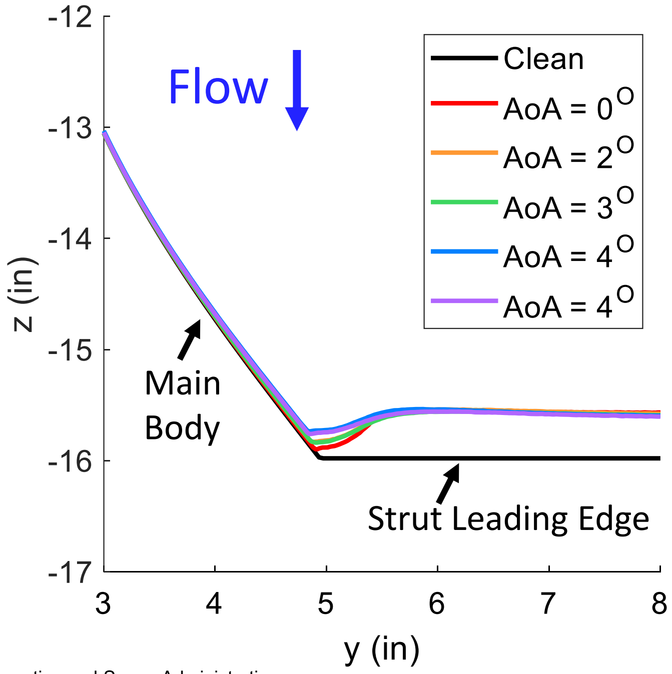
- Longer time ➔ larger ice accretion
- Double time ➔ ~ double ice mass

Target Test Conditions						Ice Accretion Measurements		
Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
Accretion Time (min)	T_0 (°C)	U (knots)	AoA (°)	MVD (μm)	LWC (g/m^3)	Both Struts Ice Mass (g)	Main Body Ice Mass (g)	LE Ice Vol. (cm^3)
5	-17	150	4	18	0.45	33	105	35.5
10	-17	150	4	18	0.45	73	208	66.5



Supercooled Liquid Icing – Location: AoA

- Larger AoA ➔ greater shadow zones on suction side
- Larger AoA ➔ pushed initial impingement limit farther back
- Shadow and concentration regions can be seen near strut junction

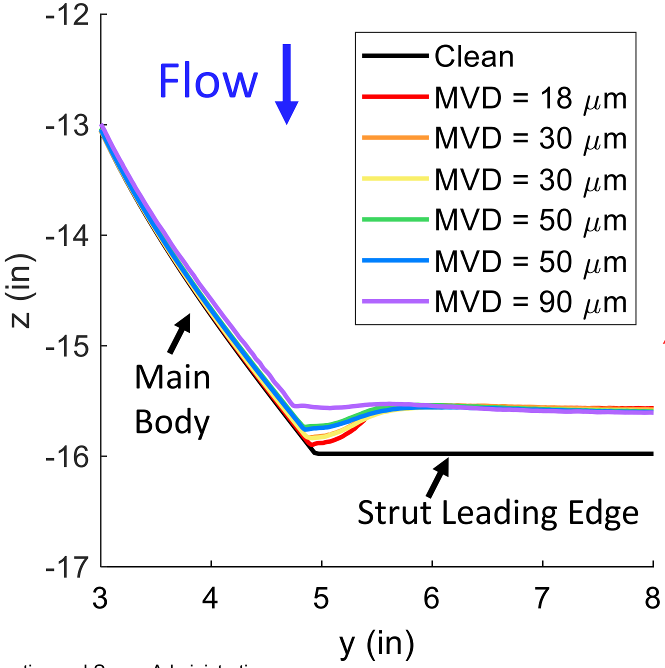


AoA = 0°   AoA = 2°   AoA = 4°

T_0 = -17 °C, MVD = 30 μm, U = 150 knots

Supercooled Liquid Icing – Location: MVD

- Smaller MVD ➔ greater shadow zones on suction side
- Smaller MVD ➔ pushed initial impingement limit farther back
- Shadow and concentration regions can be seen near strut junction



MVD = 18 μm

MVD = 90 μm

T_0 = -17 ^{O}C, U = 150 knots, AoA = 4°

Supercooled Liquid Icing – Characteristic: T_0

- Warmer T_0 ➔ glaze ice
  - Ice more transparent with horn geometries at leading edges
  - More feather shedding
- Colder T_0 ➔ rime ice
  - Ice more opaque, white with streamlined ice geometries
  - Less feather shedding

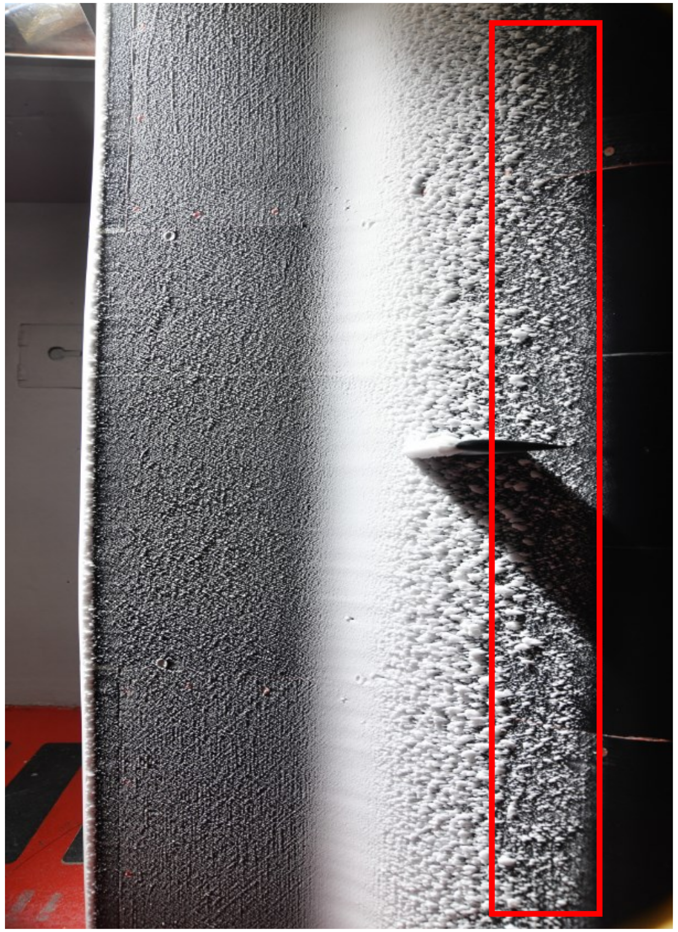
T_0 = -3 ^{O}C

T_0 = -17 ^{O}C

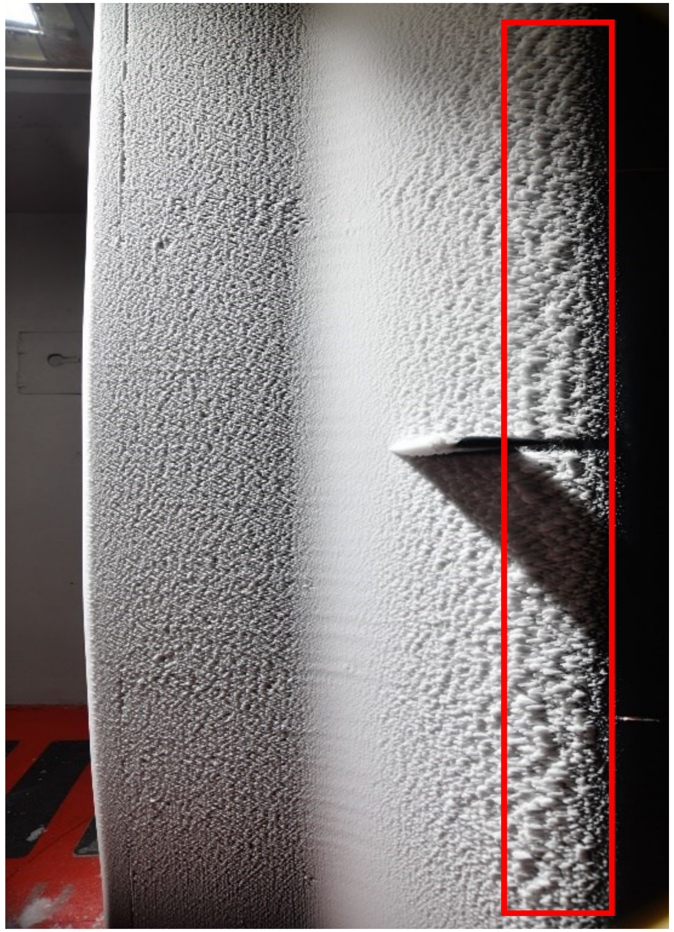
MVD = 30 μm, U = 150 knots, AoA = 4°

Supercooled Liquid Icing – Characteristic: MVD

- Smaller MVD ➔ More shedding
  - MVD = 15 µm ➔ feather shedding from 4 min until end of 10 min test
  - MVD = 90 µm ➔ no shedding



MVD = 15 µm

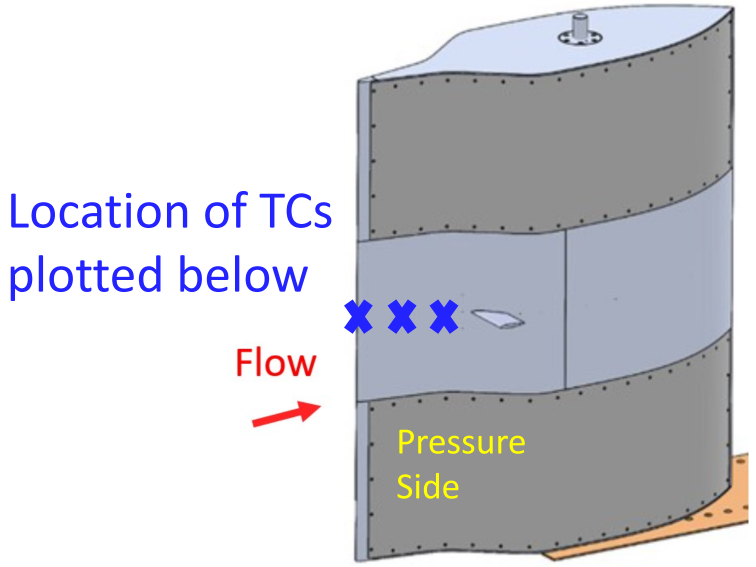


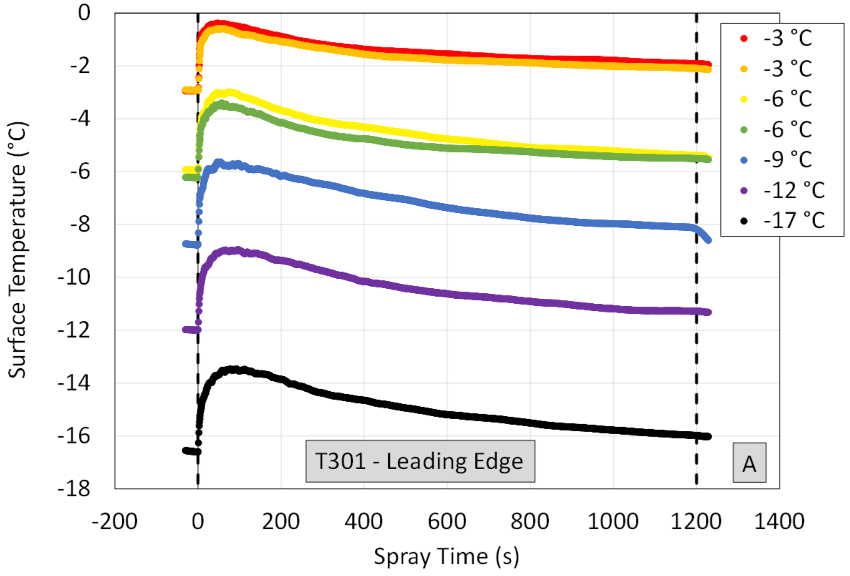
MVD = 90 µm

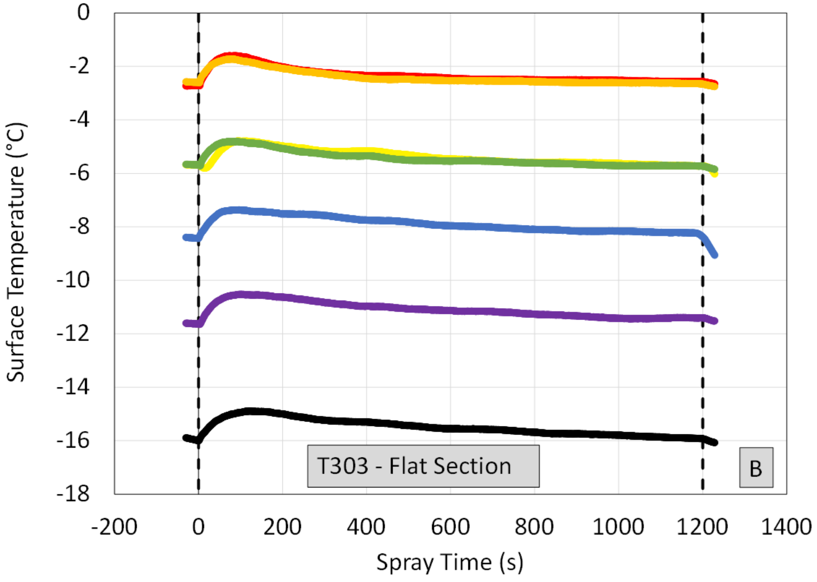
T_0 = -17 ^{O}C, U = 150 knots, AoA = 0°

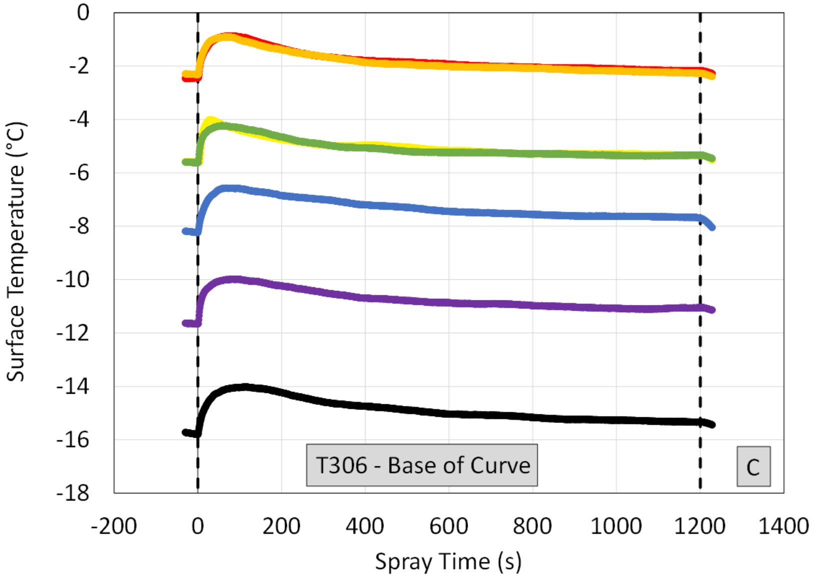
Supercooled Liquid Icing – Surface Temperature: T_0

- Initial increase in surface temp due to latent heat release from freezing
- Decrease in surface temp due to thicker insulating ice layer
- Greater surface temp increase for colder T_0 as latent heat released more quickly (freeze fraction for rime > glaze)
- Amount of surface temp increase related to collection efficiency (LE > Base of Curve > Flat Section)
- Good repeatability for T_0 = -3 and -6 ^{O}C test pairs







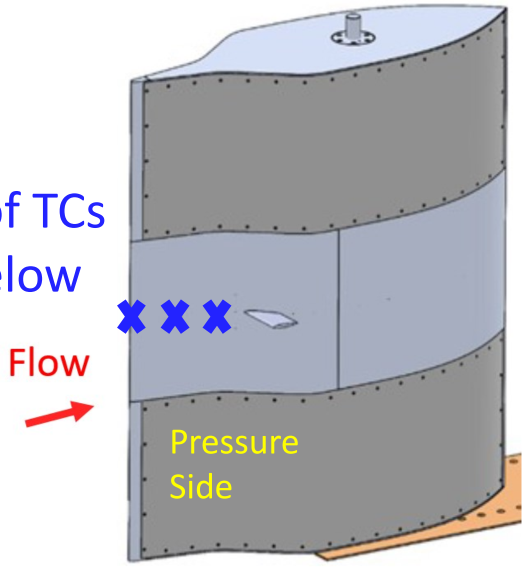


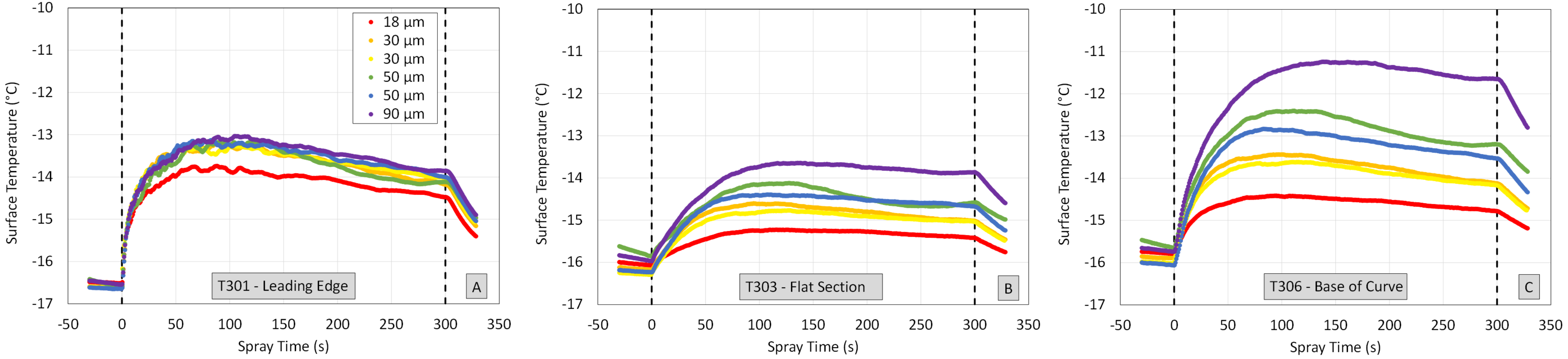
MVD = 25 μm, TWC = 0.5 g/m^3, U = 150 knots, AoA = 4°

Supercooled Liquid Icing – Surface Temperature: MVD

- Initial increase in surface temp due to latent heat release from freezing
- Decrease in surface temp due to thicker insulating ice layer
- Greater surface temp increase for larger MVD (related to collection efficiency)
- Amount of surface temp increase related to collection efficiency (LE > Flat Section)
- Good repeatability for MVD = 30 and 50 µm test pairs

Location of TCs plotted below





$T_0 = -17\ ^{O}C$, TWC = 0.45 g/m^3, U = 150 knots, AoA = 4°

Summary

- A series of component-level icing tests utilizing SIDRM were conducted at NASA IRT in 2022
  - Primary objective to collect icing data to develop and validate GlennICE accretion models
- Aerodynamic analysis: Data in good agreement with CFD simulations for various AoA and airspeeds
- SCL icing analysis: Various parametric sweeps conducted to measure impact on ice accretion size, location, characteristics, and test article surface temperature
  - Larger cloud MVD, colder air temperatures, smaller angles of attack, and longer spray times resulted in larger ice accretions
  - Test article angle of attack and cloud MVD impacted the location of ice accretion
  - Total air temperature and cloud MVD impacted icing characteristics
  - Total air temperature and cloud MVD impacted surface temperature during ice accretion
  - Good repeatability where test runs duplicated

Acknowledgments and Contact

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